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THE BROWN HARD-BACK GRUB IN ANTIGUA.

(*LACHNOSTERNA ANTIGUAE*, ARROW.)

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The brown hard-back grub in Antigua appears to have been entirely unknown as a pest until somewhere about 1911, when attention began to be drawn to it At first it was noticed only in connexion with the failure of sugar-cane cuttings to grow when planted, and afterwards it was observed in connexion with growing and ripening canes that were diseased, or stunted, or that entirely died out. At the end of 1911, a field of onions of about 7 acres was entirely destroyed by this insect, and since then it has been recognized also as a pest of Indian corn, sweet potatoes, and yams.

When attention was first directed to this insect in cane fields, it was never found in any considerable numbers, but it was always associated with canes that were in a condition to attract attention. In the case of the young plants, it will be realized that a very few grubs in the soil about a cane cutting

would be sufficient to prevent a development of healthy roots and shoots, but when only a few grubs occurred in the soil at the roots of a large well-grown cane, it would not appear that they were sufficient to cause any considerable amount of injury. In the case of a crop like Indian corn and onions, it was very easy to associate the presence and feeding of these soil grubs with the injury to the crops.

Previous to the discovery of hard-back grubs in the soils in Antigua, root disease of sugar-cane was well known to the planters. This was attributed to the attacks of the fungus *Marasmius Sacchari.*

This root disease was known to be definitely related to what might be called bad agriculture and unfavourable conditions. The bad agriculture had resulted from the situation which existed during the depression of the sugar industry, when money was scarce and the land was starved, and the canes were being grown in a soil lacking in tilth, suffering for want of an abundance of coarse organic manures, all of which factors, acting together, produced a compacted soil in which the ordinary estate drainage was insufficient in times of excessive rainfall, and which suffered, also in direct consequence of these conditions, in times of prolonged drought.

Much improvement has been brought about in Antigua as a result of better cultural methods during the past twenty years, but there is a tendency at the present time in certain localities to refer to grub attacks as being responsible for the condition of sugar-cane, when they present the typical appearance known for so long as root disease. There is no doubt that the destruction of the roots by insects would produce the same effect in the general appearance of a plant as if the roots were destroyed by a fungus, or as if they had been killed by asphyxiation resulting from insufficient drainage, or from the effects of drought. In those cane fields where the brown hard-back grub attacks the sugar-cane roots, this insect probably contributes, and perhaps contributes in some considerable degree, to produce the condition referred to as root disease. At the present time, however, there is no indication of the extent to which insect injury contributes to this result, and until agricultural methods in Antigua have done away to a very considerable extent with other influences which produce the root disease condition, it will not be possible to say how much of the injury is due to the attack of these insects. It seems certain that in some cases the feeding of the number of insects that are found in the soils of sugar-cane fields must cause injury to the canes, but there are some surprising anomalies indicated by the investigations that have been carried out up to the present time. Hard-back grubs have been found in great abundance in the soil about the roots of badly diseased canes, but in nearly every instance there have been other conditions which might well have caused all the injury to the canes, and in other cases the number of grubs found at the roots of canes which appeared to be in perfect health, showing no sign of disease or unfavourable environmental condition, have been so great as to cause wonder that no injury was apparent.

There would appear to have been a general development of soil grubs as pests of sugar-cane in different parts of the world within the past few years. In Barbados, the attacks of the root borer (*Diaprepes abbreviatus*) attracted attention in 1910, and at that time improved cultural methods were recommended for the control of this insect, and in one instance at least where these recommendations have been carefully followed, an estate which suffered badly from root borer attacks in 1910 and 1911, has since that time been entirely free from such attacks. Much attention has been given to this pest, and in connexion with this work, the Barbados brown hard back (*Phytalus smithi*) has come into some prominence. Up to the present time, however, Barbados planters do not seem to have formed any precise opinion as to the amount of damage that is being done in fields of sugar-cane by the brown hard-back.

In the annual reports of the Barbados Department of Agriculture, and the report on the sugar-cane experiments in Barbados, references are to be found to the injuries caused by the root borer and hard-back grubs to the sugar canes grown in the experimental plots, where they have occurred in such numbers as to be considered as having seriously interfered with the results of the experiments. The references to the root borer grubs in the experiment plots are to be found in each report from 1912 to the present time, while the hard-back grubs are referred to only from 1914 on.

In Mauritius, *Phytalus smithi* has been known as a serious pest in sugar cane fields since 1911. In that colony considerable sums of money have been spent, and legislation has been enacted by the Government for the control of this insect, and to prevent its spread.

In St. Kitts, the brown hard back (*Lachnosterna patruelis*) was discovered in 1912, and, while it has not occurred in great numbers, there has been a tendency on the part of some planters to refer to the attacks by this insect as explaining a diseased condition in sugar-cane.

In recent years also, other soil grubs, closely related to and of similar habits to these brown hard-back grubs have attracted greatly increased attention in Porto Rico, in the United States, in Canada, and in Australia.

So far as these insects have been observed in the Lesser Antilles, they have not been responsible for any characteristic appearance or condition of growing sugar-cane ; but in Mauritius, where it is reported that entire fields of growing canes are entirely killed out, and in Australia, where root injury is said to be so severe that strong, well-developed canes are blown over in heavy winds, there would seem to be very definite forms of injury to be ascribed to these pests.

The knowledge so far obtained of the brown hard back in Antigua has been derived from the observations by Dr. Tempany, when Superintendent of Agriculture for the Leeward Islands ; of the present writer during brief visits in 1911, '12, '14, '16, '19, and a more extended one of several weeks in 1920 ; and of those of Mr. E. S. Eldridge in 1919 and 1920.

After the visit of the writer to Antigua in March 1919, arrangements were made for Mr. Eldridge, then second assistant on the Staff of the Botanic and Experiment Station, to pay weekly visits to the estate in that island where most of the observations on this insect had been made. This estate is referred to in this paper as estate A. Mr. Eldridge also worked with the writer during the 1920 visit, and in addition has made a number of interesting observations on the life-history of the insect, both in captivity and in the field, all of which are made use of in the preparation of this paper.

The examinations by Mr. Eldridge on his weekly visits were made in three cane fields regularly—one of plant canes, one of first ratoons, and one of second ratoons. In each of these fields a hole 2 feet square was dug in a bank, a similar hole in a bar, and an unhealthy plant was dug up in each field on each visit. The soil taken from these holes, and at the base of the cane plant that was removed, was carefully examined, and a record made as to the number of brown hard backs found, whether as grubs, pupae, adults or eggs; and in the case of the larvae, notes were made on the size, and on their general condition. These weekly visits commenced on May 20, 1919, and extended to January 2, 1920.

In the field of plant canes, the number of examinations made was twenty-five, and altogether 264 grubs were found. Of these, 148 or 56 per cent. were found under the unhealthy plant, and 116 or 44 per cent. were found in the soil of the bank and bar. Under the plant, which was an unhealthy plant in its general appearance, the numbers of insects found ranged from none to fifteen. In twenty instances of the twenty-five, the number was less than ten.

In the field of first ratoons twenty-six examinations were made, a total of 734 insects being discovered, of which 425 or 58 per cent. were found under the unhealthy plants, the numbers ranging from none to thirty for each plant. In this field, 309 insects or 42 per cent. were found under the bank and bar.

In the field of second ratoons, in twenty-seven such examinations there were found altogether 849 of these insects, the number under the plant being 552 or 65 per cent. of the total, the numbers ranging from none to sixty under each plant. Of those found in the other situations in this field, twenty-seven or 15 per cent. were in the bank and 20 per cent. in the bar, the numbers in these situations ranging from none to thirty.

The figures relating to the number of grubs taken from the soil under and about the unhealthy plants in these three fields are the ones of interest at the present moment. For instance, in the case of the twenty-five unhealthy plants dug up and examined in the field of plant canes, it would not appear that there was in any instance a sufficient number of grubs present to account for very serious injury to a stool of healthy and vigorous sugar-cane, and in those instances where there was less than ten grubs per cane stool, it is hardly to be expected that their feeding would have had any appreciable affect on the condition of the canes. In the case of the twenty-five unhealthy plants examined in the first ratoon fields, no grubs were found at the base of four of them,

three others had less than ten, and in the case of thirteen others the numbers ranged from ten to twenty, and in the case of five the numbers are over twenty, with thirty as a maximum.

In the case of three of these unhealthy plants in the second ratoon field, no grubs were found, six gave less than ten each, six others twenty or under, while the remainder ranged up to a maximum of sixty each.

During the writer's visit—January- March 1920—the examinations of the soil in connexion with the grub examination was made by digging out the entire cane hole on an area occupied by a stool of canes and down to the subsoil, or as far as grubs or pupae were found, so that in a field where the lining was 4½ by 4½ feet, each cane hole examined meant the digging out of an area 4½ by 4½ feet. In recording the hard backs found, they are counted as grubs, pupae and adults, and the total is given as the number of grubs or insects found, on the supposition that whether grubs, pupae or adults at the time of the examination, they had all been grubs during the season, and had presumably all exercised some influence on the condition of these canes.

The number of these examinations made amounted to about 120, in addition to examination in the banks of young canes and corn fields, where the more extended examination was not considered feasible or necessary.

It would be of interest to consider some of the results of examinations in these three fields in which Mr. Eldridge carried out his series of observations during the year These were the fields of plant canes, first ratoons, and second ratoons, which may for the present be designated as fields A, B, and C, respectively.

Before proceeding with the study of the soil conditions, the writer obtained a statement from the manager of the estate as to the area of the field, the nature of the soil, and the susceptibility of the canes in each field to grub attack This information with regard to these three fields is given.

Field A. Plant Canes This is a field of 9½ acres. The soil is described as a heavy soil, with a clay subsoil Grubs are said to be always bad in this field in patches, especially in ratoons. Root disease has the same occurrence and distribution as the grubs.

In this field a very good strong stool of canes, with practically no root disease, standing on the edge of a field trench, and containing seventeen good canes in the clump, gave five grubs, fifteen pupae, and two adults, a total of twenty-two, all of which were found directly under the plant.

Another stool of canes, which was considered an average stool for the field and in which there were eleven good canes, and with some indication of the presence of root disease, gave ten grubs and four pupae, a total of fourteen, as against the twenty-two found under a much stronger and better stool.

Field B. 1st. Ratoons. This is a field of 4½ acres. The soil in this field is described as being very heavy. Root disease and grubs were very bad here in the 1917 ratoon crop, and also are bad in the ratoon crop to be reaped in 1920.

In this field three examinations were made; one good stool in a healthy patch of canes gave thirty one grubs and three pupae, a total of thirty-four. At the next examination in the same field, two holes were taken together, and the examination of the soil here gave thirty-three grubs and one pupae, a total of thirty-four from two cane holes of very bad canes attacked by root disease, the canes themselves being small with nothing to cut for reaping, and some of the shoots actually dying.

Field C. 2nd Ratoons. This is a field of 6 acres. The soil is described as being light with marly subsoil. 'It is fairly easily drained, and is never badly attacked by grubs.'

In this field seventeen cane hole examinations were made. Eight of these were in what was said to be good average canes, but the canes in this part of the field had been cut before the examination. However, the appearance of the stumps when seen a few days after the canes were cut, indicated that the conditions were not at all bad. The first four cane holes were taken in a block; four consecutive holes in the same row. From this block were taken a total of 199 brown hard backs consisting of 152 grubs, forty five pupae, and two adults. The next four were taken in the same row with intervals of about 30 feet. These gave the following: the first eighty-seven grubs and four pupae, the second seventy grubs and nine pupae, the next eighty-six grubs and four pupae, and the last thirty-five grubs and six pupae, a total of 319 insects, or an average of about eighty per cane hole. If these eight cane holes are taken together, the total number of insects would be 518, or an average of nearly sixty-five per cane hole, in a portion of the field where the canes were good for second ratoons.

The next examination consisted of two cane holes in which the canes were very bad, in the midst of a fairly bad root disease patch. The spot was selected on the edge of the canes that were still standing. One of these gave twenty-six grubs and two pupae, and the other seventy-four grubs and four pupae, the totals being twenty-eight and seventy-eight, as compared with the much higher numbers found in that part of the field where the canes had been much better.

The next six cane holes examined were chosen in the healthiest part of the field where the canes were still standing. This spot was on the western side of the field, at the foot of a steep slope or bluff where the soil was in very good condition, and the canes were uniformly very good over an area of perhaps an acre. The soil was deep loam in very good condition, with a clayey subsoil which gave excellent drainage.

The first stool of canes examined in this location was selected after considerable search, as being the healthiest stool of canes in the healthiest patch in the field. From the soil about the roots of this stool thirty-nine grubs, twenty-one pupae, and one adult were found, a total of sixty-one hard backs in the soil at the base of what would be called a perfectly healthy stool of ratoon canes. In this stool there were fifteen good, well-grown canes. This result is in strong contrast to the number of grubs found in what were called by the manager, very badly attacked canes. Five other healthy stools of canes were taken in this part

of the field, and these five examinations gave sixty-three grubs, seventy-six pupae, and nine adults.

Here we have the healthiest stool examined giving a total of sixty-one insects, and six other healthy stools a total of 209, or an average of about thirty-three per cane hole.

Another field, which may be called field D, was a field of 10 acres, in which ratoons are said always to be badly attacked by grubs. This field is situated on a slope, the eastern side being the higher, and in this part of the field the soil is light, with a yellow marly subsoil. Below this is a sink, which in times of heavy rain holds water. The soil here and to the west is very heavy and retentive, and in January 1920 was so full of water that the tracts left by the estate animals, mules and cattle, very quickly filled with water, which remained for two or three days before drying out. In this part of the field to the west of the sink, the canes were very bad, scarcely worth reaping, In this portion, six cane holes were dug out and the soil examined; the number of grubs found was sixty-four, thirty-one fifty-nine, 102, twenty-one, sixty-four—a total of 341, and an average of fifty-seven per cane hole. Two cane holes in this same part of the field gave sixty-eight insects - an average of thirty-four. These two holes were chosen as being samples of very bad canes in the midst of a very bad patch.

Two cane holes were dug on the higher land to the east where the soil was light, the drainage good, and all the canes in excellent condition. These two stools of canes were selected as being very good canes in a patch of very good ratoons. From the soil about the roots of these canes seventy-one grubs and seven pupae were found, a total of seventy-eight insects from two healthy stools of canes, as compared with sixty eight from two very bad stools in the same field.

These two bad stools were of considerable interest. They grew on the edge of a field trench; the only living roots were found in the top 5 or 6 inches of soil, but strong roots were found extending down to a depth of fully 2 feet.

The rainfall on this estate was very badly distributed in 1919, when these canes were making their growth. In the first nine months, that is to say, until nearly the end of September, the rainfall recorded was only 22 inches, and from the last few days in September until the end of the year, about 28 inches more were recorded. During the dry months the roots of these canes had penetrated deep into the soil, and had been able to maintain the canes in good condition in spite of the drought; but with the advent of heavy rains, the sink which was some 40 or 50 yards away, and on higher ground, was filled with water for which no proper run-off was provided, and the soil of the field on the slope below was maintained in a saturated condition. The deeply penetrating roots which were developed in the dry weather were killed by the excess of moisture after the rains came, and the plants in the attempts to save themselves had been compelled to develop a few surface roots, which under the conditions existing were far from being equal to the task that was imposed on them.

On other estates in the district where these grubs occur, similar conditions were found to exist. The estate which has already been dealt with (estate A) is situated near the centre of the infested area. Near the southern limit of the grub distribution, examinations were made in several cane fields. In one field of very good plant canes, in which spots of unhealthy canes were to be seen scattered through the field, average canes gave, in one instance, twenty grubs in three cane holes, and in another, twenty-four grubs in three cane holes. At one point in this field the canes were very bad ; entire stools had died out, and there were no canes for reaping here. In this very bad spot no grubs were to be found. It was a typical root disease condition where the soil was heavy and compact, and entirely lacking in tilth. The soil was holding moisture although the land had a considerable slope.

On this same estate, in another field, second ratoons, one cane hole examined gave thirty-nine grubs, and another sixty.

On another estate several examinations were made in a field where the soil was light and the drainage good, and no grubs were found In another field on this estate where the soil was very heavy and the drainage was obviously insufficient, and a considerable patch of canes presented a typical root disease condition, sixty-seven grubs and pupae were found in one cane hole. Other examinations in this same bad patch gave no grubs

On another estate not far distant from the one last mentioned, no grubs were to be found, although a considerable number of examinations were made, including several where the canes showed the typical appearance which, in the district where grubs are numerous, would have been called the results of grub attack. The soil on this estate was, for the most part, light and easily drained, but appeared to be lacking in organic matter, and the district is one which suffers from drought. In a district to the south of the grub infested localities, and on an estate not more than 3 miles in a direct line from estate A, no grubs were found This section is separated from the grub-infested district by a range of low hills. The soil is mostly very heavy, difficult to drain, and in many fields the canes presented even a worse appearance than in those fields where the grub attacks were most severe.

There could be no doubt that in this grub-free district, the condition of the unhealthy canes was entirely due to the unfavourable soil conditions, and the presence of root disease.

These instances might be multiplied from the notes made on these soil examinations during the visit in 1920. Enough has been said, however, to show that in Antigua there is no characteristic appearance of the canes to indicate attacks by soil grubs. Perfectly healthy canes have been grown in fields heavily infested with these grubs, and the soil about the roots of such stools of canes has been found to contain grubs greatly in excess of what have been found in the soil at the roots of certain very badly diseased canes in some adjoining fields. Also there is no consistency in the figures showing the numbers of grubs found in the soil at the roots of badly diseased canes, these numbers ranging from none and very few in many instances to over

a hundred in a few cases. In the infested district the figures seem to show that generally, the heavy soils, when drainage is insufficient, contain more grubs than the lighter soils ; but even in this respect the figures are not consistent, because as shown in the account of fields C and D, heavy infestations were found in the case of healthy cane stools grown in light soils under good conditions.

That the occurrence of grubs is not associated with heavy or light soils, is shown by the results of examinations on two estates just outside the grub-infested district. On one of these estates the soil was light and easily drained and no grubs were found there ; on the other, the soil was very heavy and drainage was extremely difficult, and on this estate also no grubs were found.

The same appearance of unhealthy canes was to be seen in all parts of the island where sugar-cane was grown on heavy soils and on light soils, more frequently perhaps on the heavy soils, and this unhealthy appearance could be explained in nearly every instance by ascribing it to some other fairly obvious cause, and it could not be explained with any degree of certainty in any instance, by attributing it to the attacks of grubs.

In some instances the grubs were found in such numbers as to make it seem almost certain that they must have had an injurious effect on the canes.

In Mauritius, under the law in force there for the control of hard-back grubs, if examinations in any field indicate the presence of 20,000 grubs or more per acre, it is required that the soil of that field shall be dug up and the grubs collected and destroyed.

In the fields examined in Antigua, the numbers of grubs found indicate an infestation in many fields much more severe than that set as a standard in Mauritius For instance, in field C already mentioned, the number of grubs found in ten cane holes in average and bad canes, gave an average of 32·5 per cane hole, and allowing 2,000 cane holes an acre, would give an infestation amounting to 65,000 per acre ; and in the same field six examinations gave an average of thirty-three per cane hole in exceptionally healthy canes showing no signs of attack ; the infestation per acre in this portion of the field would be at the rate of 66,000.

In field D, the infestation as calculated on the basis of six investigations averaged fifty-seven per cane hole, or 104,000 grubs per acre, while the healthy canes in the same field, as shown by four examinations, were infested at the rate of 69,000 per acre.

It may be of interest to consider the system on which canes are grown in Antigua at the present time.

On most estates in that island, the system of cropping includes plant canes, 1st ratoons, and second ratoons, in some fields at least ; while in rare instances there are probably still some fields of 3rd ratoons grown.

On those estates which are under contract to grow canes for the factory, there is practically nothing in the way of a system of crop rotation The fields are given good preparation for the

planting of the canes, and usually good application of coarse organic manure is made. The ratoon canes in normal times receive artificial manures, and when the ratoon series is at the end, the land is prepared for canes, and is returned to that crop in the next planting season. Indian corn, onions, and sometimes bean crops of one kind or another are grown in these fields, but only in the time between the reaping of the ratoons and the time when the young plant canes are too far advanced to allow of inter-cropping. Indian corn is often planted after the land is prepared and before the cane plants are put in, the corn ripening either just before, or just after the canes are planted ; and, if the weather conditions are favourable, Indian corn may be immediately planted again, and a second crop taken off before the canes completely cover the ground.

It would seem that this system of forcing the land must be responsible for the condition which produces the so-called root disease. The soil becomes compacted and quite unsuitable for the development of cane roots, when any unfavourable condition, such as extreme drought, or excessive rainfall is experienced. For the improvement of this condition, a crop rotation system has been recommended, providing for a full season's rest from canes after the first ratoon crop has been taken off, or in exceptional cases, after second ratoons. There can be no doubt, however, that great improvement would follow if the land could be rested from canes without bearing any ratoon crops at all.

The remedy for the root disease condition is better cultural methods, which include more frequent tillage, that is to say preparation for plant canes, and the more frequent application of coarse manures, which can only be made when the land is prepared for plant canes On heavy lands drainage requires most careful attention, and in addition, the introduction of a proper rotation crop at frequent intervals.

The following instances may be cited as showing that these purely cultural methods may be depended on to remove the condition which has long been known as root disease, and which in some places is now spoken of as grub attack.

In Antigua some six or seven years ago, certain cane fields were producing such poor canes that it became a question as to whether it would be profitable to grow sugar-cane in these fields any longer. The condition was that of a typical root disease condition, with stunted, unhealthy and rotten canes in which many of the shoots were dead. These fields were situated in the centre of the grub-infested district, but at that time the grubs were not known to occur in any considerable numbers

During the reaping season in 1920, the manager of the estate took the writer to see these fields. The canes were then being reaped ; they were extremely good, healthy canes, giving, it was said, a yield in one case of 36 tons per acre, and in the other of 40 tons per acre. No attempt had been made, in bringing these fields up to their present standard, to combat soil grubs or root disease as such ; but by attention to purely agricultural practice in the matter of manuring, frequent tillage, the use of green dressings, and attention to drainage, the root disease condition had been entirely eliminated.

In another instance, in St. Kitts, the writer was asked to examine the conditions existing on an estate in January 1914. This estate had formerly been maintained at a high standard of cultivation, but at that time many fields showed a typical root disease condition. The manager, however, attributed the condition of the canes in these fields to the attacks of the St Kitts brown hard back, which had been discovered in the soil of the sugar-cane fields about two years previously.

At the beginning of 1920 the conditions on that estate had not improved to any great extent, but in December 1920 a very marked improvement was to be seen. This result came about by the application, during 1920, of those remedial measures already referred to - improved cultivation, the use of increased amounts of manure, and in particular, the careful selection of planting material.

In a paper on some new West Indian species of the melolonthid genus Lachnosterna, published in the *Bulletin of Entomological Research* for December 1920 (Vol. XI, page 189) Mr. Gilbert J. Arrow describes five new species, one of which is the brown hard back of Antigua, to which he has given the name *Lachnosterna Antiguae* The other new species are *L. Jamaicensis*, *L. Montserratensis*, which are recorded from Jamaica and Montserrat, respectively ; and *L. acinosa* and *L. dilemma*, both of which are recorded from Trinidad. In this paper it is also stated that twenty-four species of this genus were enumerated in Messrs. Leng and Mutchler's list of 1914, in addition to which four species from Porto Rico have been named by Mr. Eugene Smyth (*Jour. Dept. Agric.*, Porto Rico, 1, 1917). Two other species have been assigned to the genus Phytalus.

Arrow discusses the other generic names which have been proposed or used to apply to these beetles, such as Brahmina, Holotrichia and others, as well as the newer generic name Phyllophaga which has been adopted in recent American works on the subject ; and he concludes that so far as the American species of this genus are concerned they should all be included in the genus Lachnosterna.

Including the five described by Arrow in this paper, there are now known thirty-five species of this genus Lachnosterna from the West Indian islands, many of which Arrow concludes are probably of economic importance.

The following is a translation of Arrow's description, which is based on numerous specimens from Antigua, and there is also one record of the occurrence of the species in Dominica

Lachnosterna Antiguae, Arrow.

Testaceous red body below, with the feet and antennae yellow ; cylindrical, somewhat elongate, pruinose, not shining, thorax densely and the abdomen, in the middle, sparsely yellow-haired ; head not broad, coarsely and roughly punctate, clypeus shining, excavated, bilobed ; pronotum fairly strongly not closely punctate ; broad, with the sides strongly arcuate, scarcely crenulate, anterior angles obtuse, posterior rounded ; scutellum unequally punctate ; elytra lightly moderately closely

punctate, costa and both discoidal sutures scarcely perceptible; pygidium a little more densely punctate, feet moderately slender, fore tibiae three-toothed with claws strongly toothed in the middle; antennae nine-jointed, club three-leaved.

Male, club of antenna equal in length to foot stalk, sixth article very short laminated, tarsi of hind feet longer than the tibiae.

Female, club of antennae short, tarsi of hind feet much shorter than the tibiae.

Notes on the Life-History of L. Antiguae.

The life-history of the Antigua brown hard back has not been worked out, but the following notes may serve to give some idea of the life-cycle and habits of this pest.

The sources of information are the same as in the first part of this paper The present writer has made observations or collected specimens during brief visits. from 1911 to 1919 and during a more extended visit of about two months in January, February, and March 1920.

Dr. H. A. Tempany, when Superintendent of Agriculture for the Leeward Islands, collected specimens and made observations, 1910 to 1916, and Mr. E. S. Eldridge made periodical visits to estate A (previously referred to) on which the brown hard back was considered by the manager a pest of some importance. for the purpose of making observations. These visits, in the first instance, from May 1919 to January 1920, resulted in weekly soil examinations for the whole of that period, the sequence being broken now and then by rains preventing field work on the days chosen. During the writer's visit in 1920, he was accompanied by Mr. Eldridge, and assisted by him during the whole of that visit. Subsequently similar observations were made during March and April, and Mr. Eldridge has also contributed notes on pupation, emergence, and egg-laying, as well as on the habits of feeding of the grubs.

The hard-back beetles (adults) have been taken in Antigua in March 1916, 1919. April 1915, May 1911, 1912. During the course of the observations in 1919, which began with Mr. Eldridge's visit of May 1920, adults were found in the soil in May, June and July. From July 8, the date when seven adults were found in the soil of a field of plant canes, no more adults were found until January 9, 1920, when two beetles were dug up, still in their pupal cells; they were freshly emerged, and had not taken on the characteristic colour of the beetle as it is usually seen.

The first beetles to be taken issuing from soil were those collected on March 8, when this estate was visited after dark. The beetles were collected with the aid of an electric torch.

Dr. Tempany observed a swarm of hard-back beetles in a cane field on April 27, 1916, and Mr. Eldridge reports an abundance of beetles, the numbers apparently being equal to a swarm, but acting as individuals and not as a swarm, in

the cane fields on May 18, 1920. This was after a rainfall of 1·50 inches on the previous day.

All the beetles collected from January 29 to March 8 in this season's work, were either in the pupal cells, or at such a depth in the soil as to indicate that they had not yet left the soil, even though they may have escaped from the pupal cell. No pupae were found from the time the observations commenced in May 1919 until late in January 1920. Pupae had been previously found in March 1919. Eggs of the hard-back were found in the soil in May and July 1919. Grubs have been found in the soil during the entire year from May 1919 to May 1920, and at all times there have been full-grown larvae whenever soil examinations have been made. Very small, small, and half-grown larvae are recorded from May to September 1919, and small larvae began to be found again in May 1920.

The evidence so far obtained indicates that while grubs, apparently full-grown, are present in the soil in the infested district in Antigua at all times of the year, there is a very definite season for pupation and for the transformation of the pupa to the adult. The actual time for the adults to come forth from the soil appears to depend on the advent of rains sufficient in amount to soften the surface of the soil.

The parasite wasp, *Tiphia parallela*, has been found in Antigua. The adults are to be seen at times in some numbers, but evidences of parasitism are very few. Hard-back grubs with parasite larvae attached were found only twice : one on January 29 and one on January 30, 1920, in the course of the series of the soil examinations carried out on one estate in May 1919 to May 1920. Adults have been observed in any number on this estate only a few times during January, February and March, and Tiphia cocoons have been found in the grub-infested soil.

During the year's observations under review, nearly 4,000 grubs have been collected on this estate, and only two of the grubs have been definitely parasitized. On eleven other estates where grubs were found in the soil, 333 grubs were collected with only one instance of parasitism being found, while in one other case, a parasite larva, presumably Tiphia, was found in the soil, not attached to its host.

Two tables are given herewith, which show in concise form the results of the observations on estate A during the year 1919-20. The first, Table I has to do with the periodical visits from May 1919 to January 1920 ; while the second, Table II, records observations made during 1920, including seven night-visits for the collection of the beetles.

TABLE I.

WEEKLY VISITS, MAY 20, 1919 - JANUARY 2, 1920.

Date of visits.	Number of grubs.	Notes.
1919.		
May 20 ...	59	Two beetles and two eggs.
„ 27 ...	62	One beetle and five eggs.
June 4 ...	69	Three beetles.
„ 10 ...	24	
„ 17 ...	32	Skeletons of beetles.
„ 24 ...	78	Some of these grubs very small.
July 1 ...	88	One adult.
„ 8 ...	49	One adult.
„ 15 ..	37	Some of these grubs small.
„ 23 ...	138	
„ 29 ...	101	Some of these grubs small.
Aug. 5 ...	103	Grubs of various sizes.
„ 12 ...	99	Grubs large and small.
„ 19 ...	77	„ „ „ „
„ 26 ...	88	Grubs half-grown to full-grown.
Sep. 3 ..	52	
„ 10 ...	98	Grubs half-grown to full-grown.
„ 16 ...	59	Grubs small to full-grown.
„ 24 ...	77	Small grubs continue to be found, especially in ratoons.
Oct. 7 ...	48	
„ 22 ...	66	
„ 29 ...	75	
Nov. 5 ...	78	
„ 26 ...	184	
Dec. 4 ...	90	
„ 22 ...	38	
1920.		
Jan. 2 ...	33	
26 visits ...	2,002	

Table II.

VISITS DURING JANUARY, FEBRUARY, AND MARCH 1920.

Dates of visits.	Grubs.	Pupae.	Adults.	Notes.
1920.				
Jan. 14 ...	12			
,, 19 ...	341			
,, 23 ...	46	1		
,, 24 ...				
,, 27 ...	71	7		
,, 29 ...	278	23		
,, 30 ...	670	118	5	
Feb. 6 ...	122	17	2	
,, 9 ...	117	71	10	
,, 17 ...	55	4	3	
,, 18 ...	157	2	1	
,, 19 ...				
Mar. 5 ...	9	1	11	
,, 8 ...				Night.
,, 12 ...				,,
,, 19 ...			9	,,
,, 23 ...			2	,,
,, 26 ...	5	2	24	
April 21 ...			1	Night.
,, 22 ...			1	,,
,, 27 ...	40	2	44	Dead beetles in soil. Adults not in cells.
May 4 ...	15		60	Many of the beetles still in cells
,, 18 ...			293	Night. 1·50 inches rain, May 17
	1,938			May 4, one egg was found.
16 day 7 night				On April 27, and May 4, small grubs began to be found, indicating that the eggs of the new generation had already begun to hatch.
23 visits				

Eggs of the brown hard back have been found in the soil of cane fields in Antigua, and have been obtained from beetles in captivity, but no records are yet available as to the length of time spent in the egg stage by this insect, nor as to the length of time during which the female beetle is capable of laying eggs.

Trials have been made in rearing the insect from egg to adult, in confinement in Antigua, but no successful rearing has yet been reported.

The available records, based on experience with very few individuals, indicate that the insect spends some three to five days as pre-pupa, and from seventeen to twenty-five as pupa. Newly emerged adults, if exposed to light, acquired the characteristic testaceous red colour in two days.

Adults appear to remain in the pupil cell for some time, making their way out and to the surface of the ground, after a rainfall sufficient to soften the soil.

Several trials have been made to endeavour to learn whether living plant material (living roots) is necessary for the food of this insect, and in several instances the indications were that decaying cane trash was preferred to the roots. Field observations suggested the same conclusion, since under certain conditions, the grubs have been found in greater numbers where there was an abundance of decaying matter than where there was a plenty of living roots without decaying organic matter.

The only direct control measure which so far has seemed to promise any considerable reduction in the numbers of this insect in the cane fields in the infested area of Antigua, is the growing of a trap crop of maize, and collecting the grubs from the soil when the corn is pulled. Corn planted in fields known or suspected to be infested with grubs, is pulled whenever attack becomes noticeable from the condition of the corn plants. In this way, on estate A, thousands of the grubs have been collected and destroyed

The following table gives figures showing the numbers of grubs destroyed in certain fields in 1918 and 1919.

TABLE III.

NUMBER OF GRUBS DESTROYED IN CONNEXION WITH THE GROWING OF TRAP CROPS OF INDIAN CORN ON ESTATE 'A' DURING 1918 AND 1919.

Year.	Area of field.	Number of grubs.
1918	10 acres	57,535
"	" "	7,500
"	12 "	37,000
"	14 "	25,938
"	" "	33,538
1919	16 "	25,950

It would appear that the destruction of large numbers of grubs in the soil before the planting of the canes would be of value in preventing injury to the cane crop, and in particular to the young canes.

At the present time the control exercised by the parasite, *Tiphia parallela*, on the Antigua brown hard back is negligible so far as the observations thus far made have indicated. *Tiphia parallela* is present in Antigua, and it attacks these grubs but not to any extent, and this appears to be true both in the centre of the infested area where the grubs are abundant, and on its borders where they are not present in great numbers.

In Mauritius, it was found that it was possible to establish *Tiphia parallela* on its introduction from Barbados, because of a suitable food plant for the adult Tiphias. This plant is *Cordia interrupta*, the leaves of which are provided with vesicular hairs. The adult Tiphia is not a flower visitor, but feeds normally on the sweetish secretions of aphides and related insects. The vesicular hairs of *Cordia interrupta* are said to have sweetish contents, on which Tiphias also feed.

It is suggested that the establishment of *Cordia interrupta* in the vicinity of those cane fields where the hard-back grubs occur in numbers may be of value in encouraging the spread of Tiphia in the infested area. It has also been found in Mauritius that the Phytalus beetles resort to the cordia plants and feed on its leaves.

The establishment of *Cordia interrupta* near sugar-cane fields in grub-infested districts would therefore serve a double purpose. The adult Tiphias, thus provided with a suitable food plant would be attracted to the vicinity of situations in which hard-back grubs occur; the hard-back beetles could be collected from these plants and destroyed.

At the present time, in considering the measures to be adopted for the improvement of the sugar-cane crop in Antigua, the greatest importance must be attached to those agricultural practices which will improve soil conditions. The brown hard back appears to be of very secondary importance in producing the unfavourable conditions of sugar-cane often referred to as resulting from its attacks.

The establishment of plant canes is sometimes seriously interfered with during the two or three months immediately following planting. Onions, Indian corn, sweet potatoes, and yams are frequently seriously attacked by the hard-back grubs.

Planters on whose estates the hard-back grubs are present in such numbers as to be a pest, should endeavour to keep their numbers down by the use of trap crops of Indian corn, and the collecting of the grubs.

REPORT ON THE PREVALENCE OF SOME PESTS AND DISEASES IN THE WEST INDIES, DURING 1919.

(Compiled from the Reports of the Principal local Agricultural Officers.)

This is the eleventh report in this series, the latest previous one, that for the year 1918, appearing in the *West Indian Bulletin*, Vol. XVIII, Nos. 1 & 2, 1920, p. 34.

The present report covers the period January to December 1919, and has been prepared in the same way as in previous years, from information supplied by the Agricultural Officers in the several islands.

ENTOMOLOGIST'S VISITS. The Entomologist visited Grenada during December 1918 and January 1919. Reference to this visit was made in last year's report. In March, the Entomologist visited Antigua and St. Kitts-Nevis, in connexion with hard back grubs and cotton pests, and in August a visit was paid to St. Lucia, having general reference to the prevalence of insect pests.

MYCOLOGIST'S VISITS. The Mycologist spent a week in Grenada at the end of February, for the purpose of gaining further information as to the red ring disease of coco-nuts. Some inoculation experiments were started, the results of which have been recorded in the *West Indian Bulletin,* Vol. XVIII, Nos. 1 & 2, 1920, p. 73.

In accordance with an arrangement made at the conclusion of Mr. Nowell's previous visit to Trinidad, December 1918 to January 1919, a second visit was paid in September 1919 in connexion with froghopper infestations on sugar-cane. Mr. Nowell's report, embodying the conclusions reached during this visit, appeared in the *Bulletin of the Department of Agriculture, Trinidad and Tobago*, Vol. XIX, Part 2, 1920, p. 52.

Remarks on Climate.

AMOUNT AND DISTRIBUTION OF RAINFALL.

GRENADA. Rainfall at Richmond 73·09 inches, fairly well distributed.

ST. VINCENT. 109·59 inches of rain fell at the Botanic Station during the year. February and March were the two driest months, and August and November the wettest.

ST LUCIA. The rainfall for the year ranged as follows: In the driest districts from 62·25 to 73·39 inches with 144 to 259 wet days. In the wet districts from 78·78 to 122·34 inches with 187 to 295 wet days. The distribution throughout the year was very good, August and November being the wettest months.

DOMINICA. The rainfall at the Botanic Gardens was 68·03 inches, or 3·61 inches below that of 1918. The year was remark-

able on account of the prolonged drought on the leeward coast, which extended from January to June. The rainfall at the Botanic Gardens during that period was only 15·47 inches. Reports from the inland and windward districts indicated normal conditions of weather.

MONTSERRAT. The average rainfall at twenty-three stations was 55·22 inches, or about 2 inches less than the average for the previous twenty-five years. The distribution of the rainfall was normal up to the month of July, but the drought experienced in the months of August and September had an adverse influence on cotton, the staple crop.

ANTIGUA. The rainfall on the whole was good and evenly distributed, March being the driest month, and November the wettest. A rainfall varying from 10 to 16 inches was experienced during the month.

NEVIS. The early part of the year was dry, and great difficulty was experienced in getting the crops established. The rainfall for the year was 38·22 inches.

For quarter ending	March	31	...	4·71	inches.
„ „ „	June	30	...	7·18	„
„ „ „	Sept.	30	...	7·78	„
„ „ „	Dec.	31	...	18·55	„

BRITISH VIRGIN ISLANDS. The rainfall during the year was 50·36 inches.

ABNORMAL OCCURRENCES (PERIODS OF DROUGHT, WET WEATHER, WIND).

ST. VINCENT. Weather was abnormally wet during November, which caused considerable loss to the cotton crop by inducing external boll diseases.

DOMINICA. Conditions during 1919 may be accounted favourable. Torrential rains fell on the leeward coast on September 1, and again on November 29 and 30, but from an agricultural standpoint, no great harm was done on either occasion.

ANTIGUA. No definite season of drought, but heavy rains were experienced in October and November. On November 10 and 11 heavy rains fell, a precipitation of 9 and 10 inches having been measured in many places; while on November 29 a very heavy downpour occurred; between 3 a.m. and 10 a.m. 4 and 5 inches were registered, with 3·30 inches in St. John's. Very low temperature was recorded on November 11, of 59° F. at 6 a.m., and in many instances the temperature did not rise above 70° F. all day.

Lowest barometer reading for the year was 29·794 at 5 p.m. on September 2, when the centre of an incipient hurricane, evidently originating between Antigua and Montserrat, passed over the island.

There was a sharp and prolonged shock of earthquake on November 14, at about 4.20 a.m.

NEVIS. From January to June the weather was dry, and the rainfall during this period was badly distributed. The month of October was the wettest for the year, the rainfall being 8·61 inches for the month.

INFLUENCE OF WEATHER ON CROPS.

GRENADA. The weather was normal.

ST. LUCIA. The weather was exceptionally favourable for all crops, and the seasonable distribution of rainfall helped considerably towards the control of scale insects by fungus parasites.

DOMINCA. The effect of the drought experienced on the leeward coast between January and June was to delay the lime crop in this district, which in consequence, did not reach its maximum until November. Under ordinary conditions, the lime crop is at the maximum about July to August.

ANTIGUA. On the whole, the weather was very favourable for the crops, but a low rainfall in August and September, followed by heavy rains of 10 inches approximately in October, and 14 inches in November, caused a severe setback to the canes, the wet, cold soil causing root troubles.

NEVIS. On account of the irregular rainfall during the early part of the year, it was found very difficult to get the crops established, and both the cane and cotton crops were late. The heavy rains from September on were of great benefit to the cane crop, but were much against the cotton crop, as they caused boll-dropping and chilled bolls.

BRITISH VIRGIN ISLANDS. Very favourable weather conditions were experienced in the British Virgin Islands during 1919, and the prevalence of insect pests may be said to have been less severe than in any previous year.

PART I. - INSECT PESTS.

Sugar-Cane.

MOTH BORER (*Diatraea saccharalis*).

GRENADA. Present. Attack local, and in some instances severe.

ST. VINCENT. Damage done much less than in previous years

ST LUCIA. Generally distributed; no serious damage reported.

ANTIGUA. Generally present in all cane fields, especially those carrying young sprouts.

ST. KITTS. Moth borer has been observed in all districts, but there has been no definite increase in its attacks during the past year.

NEVIS. Occurred in some places to a fairly great extent. Observed throughout the island, but generally, not so severe as in the past.

BRITISH VIRGIN ISLANDS. Generally distributed.

WEEVIL BORER (*Sphenophorus sericeus*).

GRENADA. Not observed.

ST. LUCIA. Generally distributed, but not serious.

ANTIGUA. Generally present in all cane fields, but cannot be considered a serious source of loss.

ST. KITTS. This insect only occurs in rotten canes, and no case of any distinct damage to growing crops has been observed.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. No record of its presence during the year.

ROOT BORERS (*Diaprepes abbreviatus*).

GRENADA. Present.

ST. LUCIA. Present, not severe.

ANTIGUA. Not observed since 1917.

ST. KITTS. This has not been observed in St. Kitts.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. Generally distributed in all districts.

(*D. famelicus*, var. *esuriens* [Exophthalmus esuriens]).

GRENADA. Not observed.

ANTIGUA. Adults of *Exophthalmus esuriens* were fairly common in cane fields. Not held responsible for much damage.

ST. KITTS. The beetles are found in large numbers in the heart of the canes, and on the cotton plants, but there has been little damage from the attacks of these root grubs as a general rule

NEVIS. Adults observed on hedges in the neighbourhood of cane fields, but grub not observed.

BRITISH VIRGIN ISLANDS. No record of its presence during the year.

CANE FLY (*Delphax saccharivora*).

GRENADA. Not observed.

ANTIGUA. No observations made.

ST. KITTS. Nil.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. No record of its presence.

WHITE ANTS OR TERMITES.

GRENADA. Present. Not observed.

ANTIGUA. Generally distributed in ratoon fields, but doing very little damage.

ST. KITTS. There has been no report of any damage from these insects, and at the Pond estate where they were formerly abundant there is a marked freedom from them.

NEVIS. Not observed as a pest of sugar-cane here.

BRITISH VIRGIN ISLANDS. No record of its presence.

HARD BACK GRUBS.

GRENADA. Not observed.

ANTIGUA. *Lachnosterna* sp. (Antigua brown hard back) were found in large numbers in the heavy fields of the central plain of this island. Undoubtedly the grubs of this pest are responsible for a certain amount of damage to young growing plants, and to ratoon sprouts ; but it is believed that the present loss attributed to this pest would be considerably lessened, if better cultivation and drainage were accorded to the fields in which the grubs were found to exist.

Ligyrus tumulosus were also found in newly manured fields, but no damage to canes has been attributed to them.

ST. KITTS. The brown hard back (*Lachnosterna patruelis*) is very common, and, where conditions are adverse, considerable damage is done, especially is this so when Marasmius attacks the cane.

NEVIS. (*Ligyrus tumulosus*) observed in fields during preparation, and in manure heaps, but not considered harmful to growing crops.

COTTON.

COTTON WORM (*Alabama argillacea*).

GRENADA. Cotton worm attacked cotton in Carriacou in August.

ST, VINCENT. Severe attack late in season on some estates in the southern part of the island.

ST. LUCIA. There was a sharp and severe attack of the cotton worm on one estate, but it was controlled by insecticides

MONTSERRAT. Attacks of this insect were mild until late in the season. Large areas, however, were denuded of growth in the month of November. At this stage of growth, on account of the uncertain prospects of securing a second picking of cotton, planters hesitate to attempt the thorough control of the pests.

ANTIGUA. Severe attacks of caterpillars were experienced throughout the island towards the close of the year, causing considerable loss to growers.

ST. KITTS. The cotton worm was prevalent towards the end of the year, but little damage was done, as insecticides were used. London purple was not found so effective as in past years.

NEVIS. The cotton worm was very severe in its attacks during the year. The insects first made their appearance as early as June, but the most severe attacks were during the month of October. The attack was perhaps the most severe on record, and a considerable amount of damage was done to the crop.

BRITISH VIR GIN ISLANDS. Very moderate attacks were recorde during the year.

BOLLWORM (*Heliothis armiger*).

CORN EAR WORM (*Laphygma frugiperda*).

GRENADA. Boll worms attacked cotton in Carriacou in August.

MONTSERRAT. Neither of these insects is recognized as a pest of cotton in Montserrat.

ANTIGUA. The boll worm was not observed during the year. The corn ear worm was not observed to attack cotton bolls during the year.

ST. KITTS. The boll worm has been observed in a few instances, but no actual damage was done.

NEVIS Boll worm not observed.
Corn worm observed in many fields of cotton, causing the loss of a large number of bolls.

COTTON STAINERS (*Dysdercus* spp.)

GRENADA. Present.

ST. VINCENT. On the whole, little damage was done by stainers. The attacks increased in severity towards the end of the season

ST. LUCIA. Cotton stainers were present, but occasioned no serious damage.

MONTSERRAT. Not so prevalent as in previous seasons, taking the island as a whole. Severe losses resulted in certain districts on the second crop of cotton, notably at O'Gara's. The proportion of stained cotton in the 1919 crop was 3·4 per cent. compared with 5·8 per cent. in the previous year

ANTIGUA. *Dysdercus andreae* appeared in large numbers late in the year. Means of control by trapping were put into practice, and, as a result, internal boll disease was not so prevalent.

ST. KITTS. Cotton stainers were conspicuous by their absence, and much less damage was done than in past years. They only appeared during the second picking about December. This appears to be due in a great measure to the campaign against the native food-plants of this insect.

NEVIS. The attack of stainers this year was later than usual and not so severe as in past years While the attack was fairly general throughout the island, on account of the attack being late, not much damage was done by this pest, and it was chiefly the second crop that was d maged.

BRITISH VIRGIN ISLANDS. Very severe attacks.

BUSH BUGS. (*Nezara viridula*, and others).

GRENADA. Present.

ST. VINCENT. Generally present. Well controlled by egg-parasites.

MONTSERRAT. These insects are invariably present in small numbers in the early part of the season, and unquestionably are responsible for a small proportion of stained cotton.

ANTIGUA. Common in all cotton fields, and are believed to be responsible for part of the stained cotton reaped, by injuring the bolls in a similar manner to stainers.

ST. KITTS. No report of any damage.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. *Nezara viridula*, locally.

BLACK SCALE (*Saissetia nigra*).

WHITE SCALE (*Hemichionaspis minor*).

GRENADA Present.

ST. VINCENT. Present in fair numbers towards the end of the season. More common in the leeward than in the windward districts.

MONTSERRAT. Practically non-existent on the Montserrat cotton.

ANTIGUA. Both always seen on the old cotton plants, but not believed to be harmful.

ST KITTS. Only seen in a few cases, not sufficient to cause any alarm, and the plants were at once turned in.

NEVIS. Not so prevalent as in the past.

BRITISH VIRGIN ISLANDS. Black scale not recorded. White scale recorded as present.

FLOWER-BUD MAGGOT (*Contarinia gossypii*).

GRENADA. Not observed.

MONTSERRAT. Not observed during the season.

ANTIGUA. Noticed on cotton late in October. Attacks increased in November, causing considerable damage to early planted cotton.

ST. KITTS. Not known in St .Kitts.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. No record this season.

LEAF-BLISTER MITE. (*Eriophyes gossypii*).

GRENADA. Present. Not doing appreciable damage.

ST. VINCENT. Nowhere serious.

ST. LUCIA. Found wherever cotton is grown, and is carried foward from year to year.

MONTSERRAT. As the result of the Close Season Regulations in force, this pest is not now regarded as a limiting agent in the amount of the cotton crop, though the pest is invariably general in its distribution towards the close of the season.

ANTIGUA. Common in all cotton fields. The severity of this pest is on the decrease, due to the enforcement of the law regarding the destruction of old cotton plants.

ST. KITTS. This pest is scarcely looked upon with any alarm, as it only appears towards the close of the season. The close season for cotton has also done a great deal in eradicating this pest.

NEVIS. Fairly general throughout the island, in some places very severe.

BRITISH VIRGIN ISLANDS. Generally distributed, but not very severe.

OTHER INSECTS ATTACKING COTTON.

ST VINCENT. Bronze beetle was present in young cotton, but did no serious injury. The same applies to aphis.

MONTSERRAT. A severe outbreak of mealy-bug (*Dactylopius virgatus*) occurred on one estate in August 1919. This pest has been noticed in limited numbers for many years, particularly on second crops, and severe epidemics are likely to be sporadic.

ANTIGUA. Aphis present in very limited numbers in some fields of cotton, but are not held responsible for any damage.

ST. KITTS. In one instance cut worms gave much trouble by cutting off the young plants soon after germination. Poison baits and hoeing up the land gave good results.

BRITISH VIRGIN ISLANDS Aphis generally distributed early in the season.

CACAO.

THRIPS (*Heliothrips rubrocinctus*).

GRENADA. Present, locally severe. Least serious year since 1916. Estate fields suffering from thrips have received better cultural attention, whilst spraying with Bordeaux-nicotine has been fairly general.

ST. VINCENT. Generally present.

ST. LUCIA. Generally distributed, locally severe, particularly in low-lying lands.

DOMINICA. Present, but not in sufficient numbers to cause appreciable damage.

BEETLE (*Steirastoma depressum*).

GRENADA. Present chiefly on western side of the island. Collecting the insects by boys is steadily carried on.

ACROBAT ANT (*Cremastogaster brevispinosa*).

GRENADA. Generally distributed throughout the colony. The acrobat ant is generally associated with mealy-bugs. Tree surgery is being practised as a control measure, and in one instance crude oil is being used as an insecticide and preventive,

SCALE INSECTS AND MEALY-BUGS.

GRENADA. Present. *Pseudococcus citri* on cacao pods, and *P. nipae* on the back of cacao leaves. Associated with black ants, and reported to be retarding the fruiting of the trees.

ST. LUCIA. Mealy-bugs found on young pods and leaves during the drought on naturally drained hillsides

DOMINICA. Mealy-bugs are occasionally found clustered around the stems of young pods

BRITISH VIRGIN ISLANDS. Mealy-bugs plentiful on cacao trees and pods.

LIMES AND OTHER CITRUS.

ORANGE SNOW SCALE (*Chionaspis citri*).

ORANGE MUSSEL SCALE (*Lepidosaphes beckii*).

GREEN SCALE (*Coccus viridis*).

GRENADA. Limes in the lowlands have suffered from scale insect attacks. In Carriacou, spraying with kerosene emulsion and whale oil soap is practised the year round, chiefly for the control of snow scale. Spraying scale insects on limes is not practised in Grenada.

ST. VINCENT. General and severe.

ST. LUCIA. *Chionaspis citri*, generally present and severe in dry districts. *Coccus viridis*, generally present, not severe. *Lepidosaphes beckii*, generally distributed, fairly severe.

DOMINICA. A serious outbreak of *Orthezia insignis* on lime trees occurred in the Soufrèire district, and a minor attack of these insects was noticed on a few trees in the Lime Experiment Station.

A good representation of most other scale insects was in evidence in the Soufrière district, green scale (*Coccus viridis*), white scale (*Chionaspis citri*), and the purple scale (*Lepidosaphes beckii*) being the most numerous.

Scale insects are usually present here and there throughout the island, wherever suitable conditions occur, such as on poor cultivations, and on cultivations in the course of being established.

MONTSERRAT Lime cultivation was remarkably free from epidemics of such scale insects as the Croton bug (*Orthezia*, sp), and the green scale (*Coccus*, sp.) the scale insects usually associated with black blight under our conditions The damage resulting from the attacks of the purple scale, on the whole, appeared to be less than usual.

ANTIGUA. The following occur on all lime cultivations : *Coccus viridis*, *Chionaspis*, sp. and *Lepidosaphes beckii*.

ST KITTS. There is no lime cultivation of any extent in St. Kitts, but wherever lime trees are grown, scale insects attack them.

BRITISH VIRGIN ISLANDS. Generally to be seen on lime trees, but not severe.

Sweet Potatoes.

SCARABEE (*Cryptorhynchus batatae*).

GRENADA. Not observed.

ST. VINCENT. More prevalent in the windward than in the leeward districts. Locally severe.

ANTIGUA. Very common in lands which have been under this crop for several seasons.

ST. KITTS. This insect has been reported, but the damage done does not seem to be very grave.

NEVIS. Not very plentiful. Observed only in a few places.

BRITISH VIRGIN ISLANDS. Generally distributed.

CATERPILLARS (*Protoparce cingulata*, and others).

GRENADA. Not observed.

DOMINICA. No definite observations.

ANTIGUA. Fairly common in fields, sometimes causing entire defoliation.

ST. KITTS. No record of any attack.

NEVIS. Observed in many fields during the months of October and November.

BRITISH VIRGIN ISLANDS. Generally distributed.

RED SPIDER (*Tetranychus telarius*).

ST. VINCENT. Generally present, nowhere severe.

OTHER INSECTS ATTACKING SWEET POTATOES

GRENADA Slugs and *Nezara viridula*.

Ground Nuts.

GREEN BUG (*Edessa meditabunda*).

ST. VINCENT. Generally distributed. Locally severe.

MONTSERRAT. Cut worms (*Prodenia* sp.) attacked young ground nuts at the Experiment Station.

ST. KITTS. Ground nuts are grown to a small extent, and they appear free of any trouble.

Coco-nuts.

WEEVIL (*Rhyncophorus palmarum*).

GRENADA. Present. Observed present in all stages in trees which have succumbed to nematode attacks. Generally distributed.

WHITE FLY (*Aleyrodicus cocois*).

GRENADA. Present. One or two of these flies have been observed in the field. They do not appear to any appreciable extent, nor have injuries done by them been observed or reported.

ST. VINCENT. Generally distributed.

SCALE INSECTS (*Aspidiotus destructor*, and others).

GRENADA. Present. Generally distributed and generally severe. The seasons when rains are late cause coco-nuts to suffer very greatly from attacks. No spraying is carried out in an attempt to control this pest.

ST. VINCENT. Locally severe.

ST. LUCIA. Present where conditions of soil and weather are not very favourable to the plant.

DOMINICA. Several plants were attacked by this pest early in the year on the windward coast, and a fair amount of damage was done.

ANTIGUA. Generally present on under side of leaves. Does little damage.

NEVIS. Observed in all plantations, but chiefly on the old leaves Not apparently regarded as a serious pest.

BRITISH VIRGIN ISLANDS. Generally distributed.

INDIAN CORN.

CORN EAR WORM (*Laphygma frugiperda*).

GRENADA. Present.

ST. VINCENT. Very little damage done by this insect during the year.

ANTIGUA. Invariably present but causes very little loss.

ST. KITTS. This insect causes much trouble with the young corn, and has been observed in every district.

NEVIS. Very plentiful, and caused a great deal of damage.

BRITISH VIRGIN ISLANDS Locally severe.

BOLL WORM (*Heliothis obsoleta*).

ST. VINCENT. Noticeably less than in previous years.

BRITISH VIRGIN ISLANDS Locally severe.

HARD-BACK GRUBS.

ANTIGUA. Grubs of the Antigua brown hard-back beetle (*Lachnosterna* sp.) are responsible for considerable losses to corn crops, especially when grown between canes.

ST KITTS *Lachnosterna patruelis*, both in grub and beetle stages, has been observed.

OTHER INSECTS ATTACKING INDIAN CORN.

ST. VINCENT. Moth borer (*Diatraea saccharalis*) generally present. Not much damage done.

NEVIS. The common grasshopper did a fair amount of damage to the younger crop in some places.

ONIONS.

CATERPILLARS.

ANTIGUA. Invariably present in onion fields. Hand collecting is usually resorted to, and found to be the best method of control. *Prodenia* sp. common.

NEVIS. Did a fair amount of damage to young slips in the nursery bed.

THRIPS (*Thrips tabaci*).

ANTIGUA. Less common in fields during the year under review.

NEVIS. Occurred in nearly all the fields, but when the crop was ripening.

YAMS

SCALE INSECTS (*Aspidiotus hartii*).

GRENADA. Present. Of late, scale insects on yams have been more noticeable than formerly. Attacks, local and severe. Plants in one section, though treated in lime water prior to planting, suffered terribly from scales after being planted in the fields.

ST LUCIA. Generally present on the Lisbon and allied varieties of yams in dry districts.

ANTIGUA Invariably present, but does practically no injury.

ST. KITTS. Stored yams are attacked by this pest.

OTHER INSECTS ATTACKING YAMS.

DOMINICA. Occasionally the tubers are attacked by borers.

ST KITTS. The yams grown seem very healthy, but the cultivation is not of any extent.

GREEN DRESSINGS, BEANS, AND PEAS.

LEAF-EATING CATERPILLARS.

ANTIGUA. Crops of black-eye peas, Vilmorin's stringless bonavist, and Canavalia beans were slightly attacked.

ST KITTS. The pigeon pea worm has been very prevalent. Green dressings are not grown to any great extent.

NEVIS. Did a great deal of damage to the black-eye pea crop during the month of October.

BRITISH VIRGIN ISLANDS. Generally distributed.

BUSH BUGS (*Nezara viridula*, and others).

ST. VINCENT. *Edessa meditabunda* frequently met with in pigeon peas.

NEVIS. A great deal of damage was done by the common green bug, by sucking the young pods.

BRITISH VIRGIN ISLANDS. Generally distributed.

Plantains and Bananas.

BLACK WEEVIL BORER (*Cosmopolites sordidus*).

ST. LUCIA. Generally distributed. Serious in most places.

DOMINICA Plantains particularly are attacked by this borer, and bananas by the brown weevil borer (*Metamasius sericeus*), to a less extent.

ST. LUCIA. Present. Not serious.

LARGE BLACK HARD-BACK BORER (*Tomarus bituberculatus*).

ST. LUCIA. Generally distributed. Serious from April to June.

OTHER INSECTS ATTACKING BANANAS AND PLANTAINS.

GRENADA. Nematodes.

Tannias, Dasheens, and Eddoes

LARGE BLACK HARD-BACK BORER (*Tomarus bituberculatus*).

ST. LUCIA. Generally distributed. Serious from April to June.

ANTIGUA. Lacewing bug.

General Remarks.

ST. VINCENT. Hymenopterous egg-parasites of bush bugs fairly well distributed. Lady-bird beetles well distributed. Hymenopterous parasites on cotton worm observed. Corythuca bug severe on Castor at the Experiment Station.

DOMINICA. The Palute or Slug (*Veronicella occidentalis*). This pest eats the leaves and shoots of provision crops. It is commonly distributed, and does a considerable amount of damage, especially to peasants' gardens.

ANTIGUA. Lacewing bug (*Corythuca* sp.), very common on old Lima bean vines. Mahogany trees were again attacked during the year by the mahogany twig borer. The attacks were, however, less severe than in the previous year. Adult beetles of *Mallodon maxillosum* were found in some numbers in old sandbox trees on one estate.

ST. KITTS. Grasshoppers do much damage to young canes in early stages of growth, especially in dry weather.

Natural Enemies of Injurious Insects.

PARASITIC AND PREDACEOUS INSECTS

GRENADA. Lady-bird beetles. Lady-birds are pretty generally distributed on the southern portion of St. George's parish, and the south-western portion of St David's. They are confined to lime fields suffering from scale insects, and to coco-nut groves affected with Bourbon scale.

ANTIGUA. *Tiphia parallela* was found parasitizing grubs of the Antigua brown hard back beetle on one estate. Adults of *Campsomeris dorsatus*, *Tachytes argentipes*, and Sphegidae were observed to be present in the island during the year under review.

ST. KITTS. Jack Spaniards are very common, and help in keeping down the cotton worm.

NEVIS. Chalcis, a parasite of the cotton worm, was discovered in certain parts of the island, where over 80 per cent. of the chrysalides were found to be parasitized.

The fiery ground beetle (*Calosoma calidum*) was observed feeding on cotton worms in the New Road district.

OTHER REMARKS.

NEVIS. No serious pest except the cotton worm occurred during the year. The cotton worm did great damage to the cotton crop, and the attack was considered one of the most severe experienced

The cotton stainer was prevalent during the latter part of the year, but, as the attack was late, less damage was done than would have been the case had the attack been earlier.

PART II.—DISEASES OF ECONOMIC PLANTS.

Cacao.

ROOT DISEASES (*Rosellinia* spp.).

GRENADA. Locally distributed, but no instance of severity recorded. For quite a few years treatment of fields with white lime or with copper compound has been practised.

ST. LUCIA. Serious in the Soufriére district, and in isolated patches in plantations in the other districts. Control measures are undertaken generally.

CANKER (*Phytophthora Faberi*, Maubl.).

GRENADA. Met with in some estates. Treatment by surgical means practised. Results apparently satisfactory. Local and not severe.

ST. LUCIA. Common in most plantations throughout the island Improved cultivation is keeping the disease under control in the larger plantations.

DOMINICA. Generally distributed.

BLACK ROT ON PODS (*Phytophthora Faberi*, Maubl.).

RENADA This disease, though present, is far from being as prevalent as formerly. This is attributed to the spray-

ing of trees for thrips with Bordeaux-nicotine, which has served the double purpose of an insecticide and fungicide. Not severe.

ST. LUCIA. Common, but fairly well controlled in the larger plantations.

DOMINICA. Generally distributed; occurs particularly on Criollo and Alligator cacao.

BROWN ROT OF PODS (*Diplodia Theobromae*, Pat.).

ST. LUCIA. Well distributed, but fairly well controlled in the larger plantations.

ST. VINCENT. Observed at the Experiment Station.

DOMINICA. Commonly met with, but not present to any great extent.

ST. KITTS. Not present to any great extent.

DIE-BACK AND STEM DISEASE (*Diplodia Theobromae*).

GRENADA. Present.

ST. LUCIA. Generally distributed, but not serious where improved cultivation is undertaken.

DOMINICA. Found here and there throughout the island where cacao is being grown under unsuitable conditions, or where proper attention is not given in the matter of drainage and shelter from wind.

BRITISH VIRGIN ISLANDS. Generally noticed.

OTHER DISEASES AND GENERAL REMARKS.

ST. KITTS. There is only a small cultivation of cacao, and the trees are fairly healthy.

Coco-nuts.

BUD ROT.

ST. LUCIA. Some suspected cases are under observation.

DOMINICA. Some suspected cases were observed.

NEVIS. Occurred at one plantation, causing the loss of a few trees.

RED RING DISEASE.

GRENADA. Generally distributed and locally severe. Wherever coco-nuts are grown, and have reached the ages of from five to seven years, red ring has appeared. Measures attempted to prevent its spread by isolation are practised.

Tannias, Dasheens, Eddoes.

There has been no record of any disease during the years.

Indian Corn.

RUST (Red or Brown).

ANTIGUA. Occurs in all maize fields.

SMUT.

GRENADA. Present.

ST. VINCENT. Found occasionally, but not severe.

ANTIGUA Isolated cases found.

ROOT DISEASE.

ST. KITTS. This disease is very common, and is responsible for much loss in growing crops of corn.

ANTIGUA. Usually found attacking Indian corn when grown between young canes.

Imphee and Guinea Corn.

There is no record of any disease during the year.

Cotton.

SOFT ROT OF BOLLS (*Phytophthora* sp.).

ST. VINCENT. This did considerable damage to the cotton crop during the latter end of the year.

ST. KITTS. No appearance during the season.

MONTSERRAT. The comparatively dry reaping season was against the development of this tpye of disease, and no losses were recorded from its effects.

WEST INDIAN LEAF MILDEW (*Ovulariopsis Gossypii*, Wakef.).

ST. VINCENT. General; late in the season.

ST. KITTS. Hardly seen during the season.

BRITISH VIRGIN ISLANDS. Presence noted at the end of the season.

ANTIGUA. Generally appears on plants towards the close of the season.

NEVIS Fairly plentiful during the latter part of the year.

BACTERIAL BOLL DISEASE (External).

GRENADA. Present.

ST. VINCENT. Fairly common.

ST. KITTS. Not sufficient to cause damage.

BRITISH VIRGIN ISLANDS. Observed.

ANGULAR LEAF SPOT.

ST. VINCENT. General, but not serious.

ST. KITTS. Not present to any extent.

BRITISH VIRGIN ISLANDS. Observed.

NEVIS. Occurred throughout the island, but when the crop was somewhat advanced.

INTERNAL BOLL DISEASE.

GRENADA. Present.

ST. VINCENT. Not as serious as formerly.

ST. KITTS. Loss from internal boll disease was not appreciable, although the cotton stainer was present at the end of the season.

BRITISH VIRGIN ISLANDS. Generally distributed.

ANTIGUA. Not so prevalent as in the previous year, possibly due to abnormally dry weather, and to reduction of the number of cotton stainers during the year.

NEVIS. Fairly plentiful in a few places toward the latter part of the season, but by no means as prevalent as in the past.

OTHER DISEASES OF COTTON; AND GENERAL REMARKS.

ST. VINCENT. The physiological affection known as 'rust,' said to be due to lack of potash in the soil, was common.

ST. KITTS. The cotton was generally free from fungoid diseases.

GROUND NUTS.

No disease has been recorded during the year.

LIMES AND OTHER CITRUS TREES

BLACK ROOT DISEASE (*Rosellinia* spp.).

ST. LUCIA. Occurs where lime trees are used to supply vacancies caused by the same disease in cacao.

DOMINICA. Estates examined recently, show that this disease is being got under control, and that its spread to other trees can be prevented by isolating the infested trees.

UNIDENTIFIED ROOT OR COLLAR DISEASES.

GRENADA. Present.

DOMINICA. Collar rot on limes has appeared on several estates. On one estate grafted oranges were affected by a kind of bacterial infection immediately above the grafts.

BRITISH VIRGIN ISLANDS Generally to be seen in storm-damaged lime fields.

DIE-BACK.

GRENADA. Present.

ST. LUCIA. Occurs on badly drained, wet land.

DOMINICA. Noticeable here and there througrhout the island, especially on trees in poor soil, or where tees are exposed to the wind.

BRITISH VIRGIN ISLANDS. To be seen at the Experiment Station.

SEEDLING DISEASES.

GRENADA. Seedlings were attacked by 'wilting' and 'damping off.'

DOMINICA. Damping off occurs every season in the seed-beds. Dusting the plants on the first signs of the disease with equal parts of sulphur and finely sifted lime is a necessary measure in the control of this disease.

OTHER DISEASES OF LIMES, AND GENERAL REMARKS.

ANTIGUA. Lime cultivations in certain districts of the island ar in anything but a healthy condition. Wind-breaks ar

needed in wind-swept situations, and practically no attention is given to the growing of green dressing crops between the trees.

Sugar-Cane.

ROOT DISEASE. (*Marasmius Sacchari*, Wakker, and allied species),

GRENADA. With the exception of a 4-5-acre field, which had to be destroyed, no further record of this disease has been reported or recorded for 1919. Distribution local ; severity local.

ST. LUCIA. Generally distributed and serious on the Bourbon canes under ordinary cultivation.

ST. KITTS. This disease is prevalent in certain districts where sufficient attention is not paid to manuring and general cultivation ; but on well-managed estates, there is practically no loss from it.

NEVIS. Observed in a few places, but not to any great extent.

ANTIGUA. Common throughout the island. Attacks would appear to be more severe in fields carrying ratoon canes.

RIND FUNGUS. (*Melanconium Sacchari*, Massee).

ST. LUCIA. Occurs on Bourbon canes generally.

NEVIS. Observed in a few fields in the Batte Plane districts

ANTIGUA. Common throughout the island.

RED ROT DISEASE. *Colletotrichum falcatum*, Went).

ST VINCENT. This disease has been found in the island during the year.

ANTIGUA. Believed to be responsible for many failures in establishing good stands of canes.

PINE-APPLE DISEASE (*Thielaviopsis ethaceticus*).

ST. KITTS. Cane cuttings are affected, especially in dry weather.

OTHER DISEASES OF SUGAR-CANE, AND GENERAL REMARKS.

ST. KITTS. There has been no serious loss from fungoid diseases during the past season.

Sweet Potatoes.

GENERAL REMARKS.

ST. KITTS. Sweet potatoes are for the most part healthy, but little attention is paid to cultivation.

Onions.

BACTERIAL ROT.

DOMINICA. Generally noticeable in the store-room, but not to any great extent, when proper attention has been given in harvesting and storing.

ANTIGUA. Very little loss was sustained by this disease during the year under review.

Fungi Parasitic on Insects.

ON SCALE INSECTS.

GRENADA. *Cephalosporium lecanii* is fairly well distributed. This is readily observed by the diminution in number of the black blighted trees.

ST. VINCENT. Shield scale fungus specially noticed in some localities on mangoes.

ST LUCIA The four common species occurred as usual.

DOMINICA. Five species are known to exist in Dominica

ST. KITTS. None recorded, the weather conditions were too dry

ANTIGUA. Red-headed and sooty mould fungi fairly common.

ON ANY OTHER INSECTS.

GRENADA. *Sporotrichum globuliferum*—thrips fungus has not been anywhere observed during the year. One field where it was introduced has been sprayed for thrips. No trace of the fungus can be seen.

Phanerogamic Parasites.

LOVE VINE (*Cuscuta americana*)

GRENADA. Present

ST. VINCENT. Common on shrubs on neglected lands.

ST. LUCIA. Considerable attention was given to this pest during the year with satisfactory results.

DOMINICA. Present, but not common.

ST. KITTS. This pest is on the increase in villages, but does not interfere with plants of commercial value.

NEVIS. Spreading; observed on bread-and-cheese hedges neglected limes, and on wild bush along the roadsides.

ANTIGUA. Very few instances of this pest to be found in the island.

MONTSERRAT. There was a striking development of Love Vine late in 1919. The attacks of Love vine in this island are however, only temporary, and the pest is not known to damage seriously permanent cultivation.

BRITISH VIRGIN ISLANDS. Very common throughout the island of Tortola. The chief plants attacked are limes, sand-box trees, cotton, and pigeon peas.

MISTLETOE.

GRENADA. Present.

ST. LUCIA. Common on limes and cacao. Appreciable results have been attained in the control of this parasite.

DOMINICA. *Dendropemon caribœus*, the species which attacks lime trees, is abundant on some estates, and is responsible for much damage.

ANTIGUA. On native trees, loblolly, etc. at Long Island.

BRITISH VIRGIN ISLANDS. Noticed in slight quantities.

REMARKS ON ANY OTHER PLANT DISEASES.

ST. KITTS. Old Man's Beard (*Tillandsia* sp.) is very much on the increase, and attacks white cedar trees to an alarming extent.

SOIL SOURNESS—ITS MEANING AND SIGNIFICANCE.*

BY F. HARDY,

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PREFACE.

I. INTRODUCTORY.

II. TRUE SOIL ACIDITY AS A FACTOR IN SOIL SOURNESS.
(A) THE THEORY OF SOIL ACIDITY.

1. The meaning of the term Acid.
2. Intensity of acidity and total quantity of acid.
3. The acids of soils.
4. Colloidal substances in soils and their relation to soil acidity.
5. The measurement of soil acidity; lime requirements of soils.
6. Buffer action in soils.

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* Received for publication February 1921.

(B) THE RELATION OF TRUE SOIL ACIDITY TO PLANT GROWTH.

1. The effect of acidity on the growth of seedlings, and on the germination of seeds.
2. The effect of acidity on the beneficial micro-organisms in the soil.
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2. The origin of salts of aluminium, iron and manganese in the soil solution.
3. The special case of manganese in the soil.

V. THE ABSENCE OF ADEQUATE AERATION AS A FACTOR IN SOIL SOURNESS.

1. Oxidation processes in soils and the factors controlling them.
2. The presence of protozoa in soils.
3. Methods of detecting and of estimating oxidative activity in soils.

PREFACE.

The following article has been compiled mainly with the object of presenting to agricultural officers and students of agronomy and plant ecology in the West Indies, the main facts connected with the modern conception of soil sourness. In it the writer has attempted to explain, in as simple language as possible, the theory of soil acidity, and to review recent articles on the subject that have appeared in the various periodicals received at the Head Office of the Imperial Department of Agriculture.†

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†Since this article was prepared for the press, the writer's attention has been drawn to a paper of somewhat similar scope that has appeared in the *Journal of Agricultural Science* (Vol. XI, January 1921, Studies on soil reaction, by E. A. Fisher). The reader should refer to this paper for a fuller discussion of the physico-chemical interpretation of soil acidity, and for a critical study of the so-called lime requirement methods for estimating it

I. INTRODUCTORY.

It has long been known that certain soils suffer from a defect which is known to agronomists as *sourness*, and that in the majority of cases the remedy for this defect is liming.

To give an exact scientific definition of soil sourness, however, is by no means simple, since the term implies a somewhat different meaning to different people. This fact becomes evident when text-books on agronomy are consulted. The chief impression given by the statement that a soil is sour is that it possesses an acid reaction. In the mind, soil acidity is usually associated with conditions of imperfect drainage, such as might prohibit the proper decay of plant residues, and favour the accumulation of humus acid substances. But this attendant conception is not always conveyed by the term soil sourness, since certain well-drained moorland, and waste land soils are frequently described as sour when they contain only a small amount of humus. Thus besides organic soil sourness we have mineral soil sourness.

The accumulation of acidic substances in sour soils has furnished investigators with a simple means of detecting soil sourness in the majority of cases, for soils that turn litmus paper red, are usually described as being acid or sour. There has thus arisen some confusion between the terms *soil sourness* and *soil acidity*. Acidity, it should be noticed, conveys to the chemist a restricted meaning which does not include all that is meant to the agronomist by the less definite term sourness.

A very widespread belief has established itself in the minds of practical men, that it is the presence of free acid in sour soils that is the chief, and even the only cause of their unproductiveness. Modern research has done much to prove the fallacy of this belief, and it is the main object of this article to demonstrate how this change of opinion has come about, and how far soil acidity *per se*, is a factor of importance in inhibiting plant growth.

When the factors responsible for the infertility of sour soils are analysed, it is found that, generally speaking, the main characteristic of such soils is the lack of easily soluble bases in them. The commonest form of easily soluble base in soils is some readily decomposed compound of calcium or of magnesium, and is usually a carbonate of either or both of these elements. A deficiency of easily soluble base in a soil permits acid substances to accumulate, so that in the majority of cases such deficiency is positively correlated with true soil acidity.

It is possible to conceive, however, that certain markedly sour humus soils, such as frequently occur in swampy districts, would never lose their sourness and become fertile even if the lack of easily-soluble base in them were to be rectified by the addition of large dressings of lime. Only thorough draining along with thorough liming would improve such soils, so that their sourness is perhaps not mainly due to a lack of base, but to imperfect aeration. Under conditions of water-logging certain toxic decomposition products of plant residues apparently tend to accumulate in soils, and it is probably these toxins that are the inhibitors of plant growth in such cases rather than the less toxic organic acids that might also accumulate.

Considerations such as these indicate that it is very difficult to differentiate soil sourness from other conditions that are summated in the term infertility. It becomes evident, therefore, that some arbitrary definition of soil sourness must be adopted In this article the following definition has been chosen, and the review of the subject has been confined as far as possible within the limits of its meaning.

Soil sourness is *that state of a soil which is induced by a permanent deficiency of easily soluble base.*

The absence of easily soluble base, as has already been pointed out, allows free acids to accumulate in the soil solution. The exact nature of these soil acids will be discussed in its proper place, but it may be noticed that soil acids are either organic acids, such as might be formed in badly drained soils, or mineral acids whose formation does not necessarily depend on the absence of oxygen in the soil. A deficiency of base in a soil may allow certain salts of the metals aluminium, iron, and manganese to be liberated. These salts are in part hydrolysed by water so as to yield insoluble hydroxides and free acid. Hence a soil may become acidic because of the formation of aluminium, iron and manganese salts in it, as a result of a series of chemical changes which will be fully described later.

Sour soils as a rule, therefore, contain free acids in their soil solutions, but it does not necessarily follow from this that it is these acids that alone are responsible for the poor growth of plants in sour soils. It may be because of the mere fact that calcium is absent or lacking in sour soils that plants do not grow satisfactorily in them, for plants require calcium as an element essential to growth, and in many cases, relatively large amounts of calcium compounds are absorbed, when available, to satisfy the requirements of the metabolism of the organism.

The toxicity of aluminium salts, and to a lesser degree of iron and manganese salts, has long been known to plant physiologists. In those sour soils that owe their acid content to the hydrolysis of such salts, it may conceivably be the presence of toxic amounts of these metals in the soil solution, and not the coincident occurrence of free acid that is mainly responsible for infertility. This conception has been repeatedly brought forward in recent literature as furnishing an explanation of the unproductivity of many sour soils. Finally, soils whose sourness is due to an accumulation of organic acids, formed by the decomposition of plant residues under particular conditions, such as are imposed by bad drainage, may fail to support satisfactory plant growth simply because of the lack of proper aeration that is so necessary for the development and vigour of beneficial soil micro-organisms, and for the respiratory needs of plant roots. Furthermore, under these anaerobic conditions, toxic organic substances frequently tend to be produced, as has already been mentioned, so that the degree of oxidation, or the oxidizing power of a soil is one of the major factors concerned in its fertility.

From the foregoing preliminary discussion it becomes evident that in setting out to examine the causes of the infertility of certain soils, which, because of their general characteristics and

their acid reaction are classed as sour soils, it is necessary first to form an estimate of the possible effect which each of the individual factors might exert in its adverse influence on plant growth. In the following sections it is therefore proposed to consider each factor in turn, and to summarize the results that have been obtained in investigations into the relationships between the growth of plants and these factors, as tabulated below.

FACTORS PRESENTED BY SOUR SOILS WHICH MAY REASONABLY BE SUPPOSED TO BE INHIBITORY TO PLANT GROWTH.

1. The presence in sour soils of acids; i.e. true acidity of sour soils.
2. The deficiency of sour soils in calcium compounds.
3. The presence in certain sour soils of toxic amounts of the metals aluminium, iron, and manganese.
4. The absence in certain sour soils of adequate aeration, the low oxidizing power of these soils thus permitting the accumulation of toxic organic substances which may or may not be acidic in reaction.

Whilst this list probably includes the most important factors presented by sour soils, it is not to be supposed that it exhausts all the factors which may be responsible for their unproductiveness. Doubtless future research will reveal other factors which play a part in giving sour soils their characteristic properties, and may greatly add to our limited knowledge of possible methods of correcting soil sourness in actual practice.

II. TRUE SOIL ACIDITY AS A FACTOR IN SOIL SOURNESS.

(A) THE THEORY OF SOIL ACIDITY.

In order to understand exactly what is meant by soil acidity as the most conspicuous characteristic of sour soils, it would be advisable first to arrive at some exact definition of the term *acid*, and to learn how acidity may be expressed.

The following three sections are therefore included to enable those who are not familiar with the modern teachings of physical chemistry to obtain some conception of certain terms which frequently occur in literature dealing with the subject of soil acidity.

1. THE MEANING OF THE TERM ACID.

The elementary definition of an acid as 'a substance containing hydrogen capable of replacement by certain metals, and when soluble, having a sour taste and possessing the power of turning blue litmus red,' although it conveys a general idea of the essential characters of an acid, yet is unsatisfactory for many reasons, and fails to explain completely certain reactions in which acids are involved. Attempts to frame a hard and fast definition of the term acid were all more

or less unsuccessful until the *electrolytic dissociation theory*, first propounded by Arrhenius in 1887, came to be generally accepted.

The electrolytic theory of dissociation is based on the assumption that chemical compounds whose solutions conduct electricity (i.e. *electrolytes*), break up or dissociate into portions known as *ions*, when they enter into solution in certain solvents. Ions may consist of single atoms or groups of atoms, and they carry definite electric charges. Certain of them, for instance, ions of hydrogen and of metals, bear positive electric charges, whereas others, for instance, acid radicles such as sulphate-ion and nitrate-ion, are negatively charged. As an example, we may take the electrolytic dissociation of common salt. When this compound is put into water, it dissolves and yields a solution which will conduct electricity. In other words, common salt is an electrolyte. According to the theory, it is assumed that during solution a large percentage of the common salt molecules dissociate or *ionize* into sodium ions, bearing positive charges, and chlorine ions, carrying charges of equal magnitude but of opposite sign to those of the sodium ions. Not all the common salt molecules dissociate in solution, however, for a small percentage remain unionized, yet dissolved.

The *degree of dissociation or ionization* is the fractional amount of a compound which is ionized. For any given compound, its value depends on certain factors of which the nature of the solvent, the degree of dilution, and the temperature are the chief. The properties of ions are entirely different from those of the free elements or molecules ; sodium ions, for example, have no resemblance to metallic sodium as we know it, a fact which is accounted for by the presence of the electric charges which the ions carry, and which completely alter their behaviour. The leading properties of dilute solutions of ionizable compounds are, according to the electrolytic dissociation theory, the properties of the ions themselves. Thus, all cupric salts in dilute solution owe their blue colour to cupric-ion.

Considering the special case of acids, it is to be noted that the particular acidic properties of all members of this class of compounds are due to the fact that they yield hydrogen-ions when dissolved in water, and the acidic properties are therefore simply *those of the hydrogen-ion itself*. We may consequently define an acid, from the standpoint of modern physical chemistry, as *a compound which dissociates when dissolved in water yielding hydrogen-ions*.

The *strength* of an acid depends upon the degree of ionization which it undergoes when dissolved. Hydrochloric acid is a strong acid because, in dilute solution about 75 per cent. of its molecules dissociate into ions. Acetic acid, on the other hand, is a weak acid, since only about $1\frac{1}{4}$ per cent. of its molecules dissociate.

2. INTENSITY OF ACIDITY AND TOTAL QUANTITY OF ACID.

We must distinguish carefully between the terms *degree* or *intensity of acidity*, and *total acid*. Intensity of acidity is defined as the *hydrogen-ion concentration of* an acid solution.

Total quantity of acid, on the other hand, is the *total amount of ionizable acid* which is present either in solution, or, if insoluble, in intimate contact with the solution.

Let us consider the case of N/10 hydrochloric acid and N/10 acetic acid. If these acid solutions be separately titrated with N/10 sodium hydroxide until they each give a pink colour with phenolphthalein, 10 c.c. of each acid will require exactly 10 c.c. of the alkali, and will therefore have apparently the same acidity. Actually, however, hydrochloric acid is about sixty times as strong an acid as acetic acid, for it is capable of ionizing to a degree sixty times that of acetic acid. During the titration of an acid with an alkali, as soon as the ionized part of the acid has been removed by the alkali, a further amount of the previously undissociated acid is ionized. This process is repeated with further additions of alkali, until the whole of the acid originally present has become dissociated, and its hydrogen-ions have united with the hydroxyl-ions of the alkali. The next trace of added alkali now reacts with the indicator to give a pink colour. Titration, therefore, only gives an index of the capacity of a solution to neutralize acids or alkalies; it does not give any information concerning the intensity of acidity, i.e the concentration of the hydrogen-ions in it.

It is necessary to adopt some method of expressing *intensity of acidity*. The following considerations suggest a simple convention which is nowadays generally accepted by physical chemists. We must note first, that water itself is slightly ionized, so that in a vessel containing pure water, there are innumerable undissociated molecules of water plus a certain small number of free hydrogen-ions and an equal number of hydroxyl-ions. The concentration of hydrogen-ion in pure water at a temperature of 25° C. is approximately 0·000,000,1 gram per litre, or 1×10^{-7}. Water may therefore be considered as being a very weak acid, and, if we use it as a standard for comparing the strengths of other acids, we may define *neutrality* as a degree of hydrogen-ion concentration equivalent to 1×10^{-7} grams of hydrogen-ion per litre. The strength of a centinormal solution of hydrochloric acid, that is, of a solution of hydrogen chloride containing 0·365 gram of the compound per litre, expressed in terms of hydrogen-ion concentration, is approximately 0·00916 gram of hydrogen-ion per litre, or $9{\cdot}16 \times 10^{-3}$.

In order to obviate the necessity of writing such unwieldy expressions as $9{\cdot}16 \times 10^{-3}$ for the hydrogen-ion concentration of an acid, it is customary to use logarithmic exponents of the expressions. These are known as *pH values*. The term pH is defined as the logarithm of the reciprocal of the hydrogen-ion concentration, i.e. $\text{pH} = \log \frac{1}{\text{H-ion concentration}}$. Thus the pH value for a centinormal solution of hydrochloric acid is $\log \frac{1}{9{\cdot}16 \times 10^{-3}} = \log \frac{10^3}{9{\cdot}16} = \log 10^3 - \log 9{\cdot}16 = 3{\cdot}00 - 0{\cdot}96 = 2{\cdot}04$. Similarly for pure water at 25°C., $\text{pH} = \log \frac{1}{1 \times 10^{-7}} = \log 10^7 = 7{\cdot}00$.

The ionic dissociation of water is usually expressed by the equation $H_2O \rightleftharpoons H^+ + OH^-$, or $H_2O \rightleftharpoons H' + OH'$, the symbol H' (or H') representing a positively charged hydrogen-ion, and the symbol OH^- (or OH') representing a negatively charged hydroxyl-ion. The equation indicates that the ionic dissociation of water proceeds to an equilibrium in which, according to the well-known laws of mass action,

$$\frac{[H'] \times [OH']}{[H_2O]} = \text{constant.}$$

(The square brackets signify the concentration in grams per litre of ions or molecules respectively). Since in the case of water, the mass of undissociated water is enormously large compared with the mass of free ions produced, it can be regarded as a constant, so that [H'] × [OH'] = a constant.

We have seen that the concentration of hydrogen-ion in water at 25°C. is 1×10^{-7} (pH = 7·0), and that when an acid is added to pure water, the hydrogen-ion concentration is increased, and that this corresponds to a decrease in the pH value. Now when *an alkali* is added to water, the alkali dissociates more or less completely into hydroxyl-ions and certain positive ions. Sodium hydroxide (caustic soda), for example, dissociates in high degree when dissolved in water in accordance with the equation†, $NaOH \rightleftharpoons Na' \pm OH'$. The addition to water of more hydroxyl-ions by the simple process of dissolving some hydroxide or other alkali which will yield hydroxyl-ions in the water, will cause a lowering of the concentration of hydrogen-ion in it, as may be inferred from the equation [H'] × [OH'] = a constant; for any increase in the concentration of hydroxyl-ion must be accompanied by a corresponding decrease in that of hydrogen-ion to maintain equilibrium. We may therefore define an alkaline solution as one in which the concentration of hydrogen-ion is *less than* that of water, i.e., is less than 1×10^{-7}. The pH value for any alkaline solution is consequently greater than 7·0.

Summarizing these results we note the following definitions : –

1. A *neutral solution* is one in which the hydrogen-ion concentration at 25° C. is 1×10^{-7} grams of hydrogen-ion per litre, or for which the pH value is 7·0.

2. An *acid solution* is one in which the hydrogen-ion concentration at 25°C. is *greater than* 1×10^{-7}, with a pH value of something *less than* 7·0.

3 An *alkaline solution* is one in which the hydrogen-ion concentration at 25° C. is less than 1×10^{-7}, with a pH value of something *greater than* 7·0.

3. THE ACIDS IN SOILS.

It is now admitted by the majority of soil chemists that

† Difficulties in regard to type have made it necessary to indicate the reversible nature of the equations in this paper by 'dagger' instead of by the usual 'arrow' signs.

certain substances capable of yielding hydrogen-ions occur in most soils. The following table will serve to indicate the nature of these substances. [79].* Soil acidity is the result of an increase of hydrogen-ion concentration in the soil solution in excess of that exhibited by pure water. Such an accumulation of hydrogen-ions is due to the dissociation of soil acids in the absence of a sufficient quantity of base, for when bases are present in excess, they cause a complete suppression of hydrogen-ions because of the fact that they yield hydroxyl-ions on dissociation, and these combine with hydrogen-ions to form non-dissociated water molecules.

SOIL CONSTITUENTS YIELDING HYDROGEN-IONS.

1. *Directly (when treated with water alone).*

A. *Inorganic.*

(a) Strong, highly ionized acids, such as hydrochloric and sulphuric acids.

(b) Weak, slightly ionized acids, especially carbonic acid, silicic acids, and alumino-silicic acids.

(c) Acid salts, such as potassium hydrogen sulphate, which may be moderately or slightly ionized and yield hydrogen-ions.

(d) Salts of weak bases with strong acids, such as aluminium chloride, which react with water (i e. are hydrolysed in solution) and thus produce a moderate concentration of hydrogen-ion derived from the liberated acid.

B. *Organic.*

(a) Strong, highly ionized acids such as citric and oxalic acids.

(b) Weak, slightly ionized acids, such as acetic acid.

(c) Acid salts of organic acids.

(d) Salts of weak bases and strong organic acids, such as aluminium citrate, which are hydrolysed as in A (d)

(e) Amino-acids, such as aspartic acid.

(f) Humic acids, which if they are definitely existent in the soil, are only slightly ionized.

2. *Indirectly (when treated with solutions of salts).*

A. Inorganic, especially colloidal †clay.

B. Organic, especially colloidal †humus.

It would appear from the above list of acidic substances likely to occur in a soil, that soil acidity is a very complex phenomenon. It is probable, however, that comparatively few of these possible sources of hydrogen-ion coexist in appreciable amounts in any one soil. For example, the natural occurrence in soils of strong acids, such as hydrochloric or sulphuric acid,

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*Reference is made by number to the bibliography tabulated as an appendix to this article.

†See the next section.

is somewhat rare. The former occasionally occurs in acid soils of salt marshes, and the latter in soils rich in sulphur compounds, as for example, those which contain the mineral pyrites. Soil acidity caused by the excessive use of ammonium sulphate as a fertilizer possibly owes its origin primarily to the liberation of sulphuric acid. Nitric acid, although a strong acid, is perhaps not often directly responsible for a markedly acid soil reaction, since it is quickly changed into nitrates in soil, and these are rapidly absorbed by plants and soil-organisms, or leached from the soil if not absorbed.

Carbonic acid is universally present in soils, in which it arises from the decomposition of organic matter. Salts of aluminium and of iron may readily be formed by the action of strong acids or solutions of other salts on certain mineral silicates present in soils. Hydrolysis of aluminium and iron salts yields strong acids, which in turn give hydrogen-ion by dissociation, as represented in the equations.

$$Al\ Cl_3 + H_2O \rightleftharpoons Al\ (OH)_3 + 3\ HCl \text{ and } HCl \rightleftharpoons H' + Cl'.$$

This subject will be more fully considered in another place.

Organic acids are, under certain conditions, undoubtedly formed in soils by the action of various micro-organisms on cellulose and other constituents of plant tissues. Nitrogenous organic matter in soil may give rise to such acids as aspartic acid. Under the conditions which occur in well cultivated soil, however, organic acids are usually rapidly oxidized, and so never accumulate to any marked extent. Only in badly drained soils, or during periods of excessive rainfall may organic acids be produced in sufficient amount to cause soil acidity. The general effect of organic material appears to be, indeed, in normal solids, to keep down acidity rather than to create it, for proteins in particular act as buffers, as will be fully explained later.

Perhaps no subject connected with the chemical composition of soils has been so extensively discussed as the question of the occurrence of the so-called humic acids in soils. Without going into the details of this controversy, it may be stated that there appears to be convincing evidence to prove that humus contains one or more substances capable, under certain specific conditions, of yielding hydrogen-ions, and which may therefore be classed as acidic. Whether or no these substances are of definite composition, and contain ionizable hydrogen chemically combined, or are of indefinite composition, colloidal* in character, and contain hydrogen-ions absorbed in variable amounts, is the chief point in dispute.

The majority of soils consist of the products of weathering of rock minerals, to which have been added a certain amount of organic matter, and other extraneous material which have become incorporated with the mineral débris during the natural process of soil formation. The most important soil-forming minerals are the felspars. During weathering, felspars are first hydrated by the action of water. Hydrated minerals, such as

*For an account of the meaning of the term 'colloidal', and the bearing of colloidal substances present in soils on the question of soil acidity, the reader is referred to the next section.

zeolites, are said to result, and free silica is liberated. Thus albite, or soda felspar, may yield natrolite, or soda zeolite, and silica, according to the equation—

$$Na_2O{\cdot}Al_2O_3{\cdot}6Si\,O_2 + 2H_2O =$$

Albite.

$$Na_2O{\cdot}Al_2O_3\,3Si\,O_2{\cdot}\,2H_2O + 3Si\,O_2$$

Soda zeolite.

Some doubt has been expressed [9] as to whether or no zeolites actually do exist in soils. Whilst their presence in soils has never been demonstrated by mineralogical examination, yet many of the chemical properties possessed by soils may be simply and satisfactorily explained by assuming that they constitute the more reactive portion of the clay fraction of soils. (See 64.)

After the first stage of hydration, further changes probably occur rather rapidly, and result in the formation of other hydrated silicates of which kaolinite ($Al_2\,O_6\,2Si\,O_2{\cdot}2H_2O$) is a common example. Probably water containing carbonic acid in solution is an active agent in the later stages of weathering, removing bases such as sodium and calcium oxides from zeolites in the form of carbonates and bi-carbonates. It is possible also, that the free silica which is liberated during many of the reactions mentioned, becomes hydrated into one or more of the various weak silicic acids.

The end products of the weathering of minerals of the felspar group, whatever the intermediate stages may be, are thus seen to consist in general of alumino-silicic acids, such as kaolinite, together with various less complex silicic acids. When kaolinite forms the most conspicuous product, the weathering process is termed *kaolinization*, and in temperate climates this is the chief type of decomposition which affects the felspar minerals in rocks. Under certain conditions rock decay may, however, be even more profound. In the tropics, for example, a process known as *lateritization* frequently affects rocks rich in felspars and in iron-containing minerals. The end products of lateritization consist chiefly of various hydroxides of aluminium, such as gibbsite ($Al_2O_3.\,3H_2O$), bauxite ($Al_2O_3,\,2H_2O$), and diaspore ($Al_2O_3H_2O$), derived chiefly from felspars, together with ferric hydroxide. The presence of this latter compound usually gives to the clayey residium (laterite) a bright red colour.

Alumino-silicic acids, for example, kaolinite, and silicic acids, are more or less insoluble in water. The small proportion which dissolves, however is dissociated to some extent, and yields hydrogen-ions to a small degree of concentration. In mineral soils, therefore, there exists a large reserve of slowly reactive or potential acids, which, by reason of their limited solubility and their low degree of ionization, may impress an appreciable intensity of acidity upon the soil solution.

There occur also in soils certain minerals which may not be hydrated so as to be capable of yielding hydrogen-ions directly, but which may react with solutions of neutral salts, such as might be liberated during certain chemical changes occurring in soils, or might be added as fertilizers, so as to liberate hydrogen-ions. Thus, when potassium chloride is added in solution to a soil, the solution becomes more or less strongly acid. Although this may not be the result of a single process, yet it may in part

be accounted for, by assuming that compounds such as aluminium and iron silicates exist in the soil, and that these react with potassium chloride to form potassium silicate, and aluminium and iron chlorides. The last-named salts, as has already been stated, are hydrolysed in the presence of water, yielding hydrochloric acid, which is the direct source of the hydrogen-ions that are liberated.

4. COLLOIDAL SUBSTANCES IN SOILS AND THEIR RELATION TO SOIL ACIDITY.

It has been stated in the last section that many of the facts connected with the chemical properties of soils, and in particular those bearing on the question of soil acidity, may be explained by reference to the so-called *colloids* in soils. It would be well, therefore, to consider the nature and behaviour of soil colloids in some detail.

The term colloid does not refer to any particular substance or group of substances, but is used rather to describe a state in which any form of matter may occur. Recent research has indicated that al substances can probably be brought into the colloidal state, provided that suitable means are found for causing their dispersion.

Broadly speaking, the chief characteristic which distinguishes substances in the colloidal state, lies in the relative size of their particles. Whereas true molecules have an average diameter of about 2×10^{-8} cm., the size of colloidal particles varies between $1 + 10^{-3}$ and 1×10^{-6} cm. Substances which are in colloidal dispersion in water are neither ionized nor properly dissolved so as to give truly homogeneous systems, but the molecules are aggregated into masses which are great compared with molecular magnitudes, but which are not sufficiently heavy to settle Colloidal dispersions are therefore heterogeneous, and contain more than one phase. Consequent on the large surface area of contact between liquids containing colloidal particles and the particles themselves, the surface energy of colloidal substances is relatively very great. As a direct effect of this, colloidal systems exhibit a phenomenon known as *adsorption*, and this is perhaps the most characteristic manifestation of the colloidal state It is due to this property that colloidal particles are able to assimilate and hold at their surfaces, and with great tenacity other colloidal particles, molecules or ions. Thus charcoal, in a sufficiently fine degree of subdivision, can adsorb great quantities of various gases, or, when suspended in a liquid, can remove various substances from solution.

Adsorbtion effects, and indeed the properties of colloidal systems in general, are somewhat modified by electrical forces which act upon them. For example, when a colloidal particle adsorbs an ion or ions, the electric charges on the latter are supposed in certain cases to be given up to the particle, which thereby attains the power to repel a similarly charged particle. It is frequently by reason of the possession of electrical charges by colloidal particles which hold adsorbed ions on their surfaces, that their solutions are rendered stable. If the particles, by adsorbing other ions of opposite charge, have their charges

neutralized, the stability of the system is destroyed, and aggregation tends to proceed,

Different substances in the colloidal state exhibit different specific properties, especially as regards the adsorption of molecules or ions. Thus one colloidal substances may be able to adsorb molecules or ions of a particular kind, but not others. To this property is due to the power of *selective absorption* exhibited by certain colloidal substances.

Without going more deeply into the numerous other aspects and facts* connected with the subject of colloidal science, we may now proceed to consider the especial bearing of the subject on soils. It is not intended to discuss the rôle which substances in the colloidal state play in physico-chemical phenomena, such as the complex water-relations of soils, but to confine our attention chiefly to the question of soil-acidity.

The colloidal substances present in soils are either of organic or of mineral composition. The former occur in the humus component, and the latter chiefly in the finer mechanical fractions, which may be collectively referred to as clay. The mineral substances that are most usually found occurring in the colloidal state in soils are the products of hydrolysis of rock-forming minerals, i.e. hydrated silicates, such as kaolinite, etc., hydroxides, such as ferric and aluminium hydroxides, and hydrated silica, (or silicic acids).

It is not known exactly how these colloidal substances are arranged in soils, but there is evidence to show that they probably form a coating round the non-colloidal particles, or that they exist as a mesh-work enclosing these particles.

The capacity of the colloidal substances to adsorb water to various degrees of hydration accounts for most of the important physical characteristics of soils. As regards the special colloidal properties which, along with those already mentioned, have been indicated as furnishing a satisfactory explanation of many of the properties of soils, the following may be noted. It must be observed, however, that certain of the statements made are open to criticism, and that the reactions which they are held to explain can in many cases be equally well, or even more convincingly, elucidated by purely chemical reasoning, as will be briefly shown.

1. The more finely divided particles of soils, when dispersed in water are stated to be electro-negatively charged†. This is explained by assuming that on hydrolysis, certain potassium-bearing silicates present in it, liberate minute quantities of potassium hydroxide, and the loss of positively charged potassium-ions by the silicate particles, leaves the latter in possession of a negative charge. Since such particles possess negative charges, they are aggregated by positively charged

* For further information on the physics and chemistry of the colloida state, the reader is referred to the books and articles mentioned in the bibli ography (nos. 33, 53, 50, 59).

† See, however, the recent work of Comber (14 a) whose experiments indicate some differences between the colloidal state of the true clay fraction of soils and the finer silt fractions.

ions, such as those of hydrogen and of metals, so that solutions of acids and of salts are effective agents in bringing about the flocculation of the finely divided particles. The process is reversible, for the removal of the flocculating agent causes in general, immediate deflocculation.

2. Humus and colloidal soil-clay possess the power of adsorbing certain substances from their solutions. The substances adsorbed may be—

(a) *Ions of metals*, such as potassium-ions, which it is assumed can be withdrawn from solutions of neutral metallic salts independently of the equivalent and oppositely charged ions simultaneously liberated by the dissociation of the salt. Two well-known facts in this connexion require further attention.

(i) When neutral salts are added to colloidal clay dispersed in water, the liquid becomes acidic in reaction, showing that the hydrogen-ion concentration has been augumented.

The supporters of the colloidal theories of soil acidity* explain this result [8, 9, 31, 54,] by assuming that the salt is first hydrolysed, and yields a hydroxide plus an acid. The former is then adsorbed *as a whole* by the colloidal clay particles, and the solution is thereby left with an acid reaction. It is difficult to understand the mechanism by which the metallic hydroxide is caused to unite with the colloidal material. Further, it would appear that, if clay can bring about such a liberation of hydrogen-ions in solutions of neutral salts, then any sort of finely divided material should be capable of producing the same result, and it should be possible to obtain varying degrees of acidity, simply by increasing or decreasing the quantity and size of the dispersed colloidal particles. No convincing data have yet been brought forward to support this generalized argument, so that the colloidal explanation is somewhat discountenanced.

The result can be equally well explained on purely chemical grounds, for we may reasonably assume that the metallic hydroxide formed by the hydrolysis of the added neutral salt actually combines with some mineral constituent of the clay instead of being adsorbed by the clay.

When we consider the phenomenon in connexion with *soil* (which contains colloidal clay), we have the additional possibility that, provided easily neutralizable bases such as calcium carbonate are absent, the development of acidity by the addition of solutions of neutral salts to certain soils can easily be accounted for, on the assumption that an exchange of bases between the salt and certain insoluble aluminium compounds of the soil takes place. The soluble aluminium salt thus produced is hydrolysed, and yields hydrogen ions in a way already explained.

(ii) The second fact, although not directly connected with the question of soil acidity, is worthy of passing mention, because of its great importance in relation to the

* For a historical account of the different theories which have been formulated to explain soil acidity, the reader is referred to 'Soil Conditions and Plant Growth.' E. J. Russell, 4th Edition, 1920. *Longmans Green & Co.*, (64).

chemical properties of soils. It is the exchange of bases that goes on when solutions of neutral salts are added to certain soils. Thus, when potassic fertilizers are added to neutral or alkaline soils, the potassium is retained, and a corresponding amount of some other base, usually calcium or sodium, is liberated, and may appear in the drainage water.

This result is explained in terms of the colloidal properties of soils by assuming, as before, that hydrolysis of the salt first occurs ; that this is followed by the adsorption of the hydroxide thus produced, but that the acid simultaneously liberated, now reacts with certain bases in the soil to form soluble salts which subsequently appear in the drainage water. In this way the presence of easily decomposed bases, such as calcium carbonate, in soils, accounts for the fact that these soils maintain a neutral or alkaline reaction, even when heavily manured with fertilizer salts, such as potassium or ammonium sulphate.

As before, this type of reaction can equally well be explained without postulating a colloidal adsorption process. It has also received a satisfactory explanation for those who hold that zeolites occur in soils by the classical researches of Way, who proved that double silicates of the zeolite type can readily exchange their bases for other bases contained in neutral salts brought into contact with them, eg.,

$$Na_2O{\cdot}Al_2O_3{\cdot}3SiO_2{\cdot}2H_2O + K_2SO_4 \rightleftarrows$$

Soda zeolite

$$K_2O.Al_2O_3{\cdot}3SiO_2{\cdot}2H_2O + Na_2SO_4$$

Potash zeolite.

It appears from the above discussion that the reactions which go on when solutions of neutral salts are added to soils are of a very complex nature, involving various physico-chemical changes, and as yet no definite conclusions can be drawn as to the exact mechanism which accounts for all the known facts.

(b) *Hydrogen-ions* may possibly in certain cases be retained in an adsorbed condition by the colloidal particles in soils. In this condition they are said to be replaceable by metallic ions introduced into the soil by the addition of neutral solutions of salts, and certain authorities consider this to be the most important source of indirect acidity as induced by the addition of salts to soils. [79].

(c) *Hydroxyl-ions*. Sharp and Hoagland [69] have shown that hydroxyl-ions are removed by certain soils from added solutions of metallic hydroxides, such as those of potassium, sodium, barium and calcium. The experimental results indicate that selective adsorption occurs, for apparently a relatively greater amount of hydroxyl-ion is removed by soils from the two last-named hydroxides than from the first two. These results are interpreted as being due to the simultaneous removal of both positive and negative ions from the hydroxide solutions. They may be explained either as colloidal phenomena dependent on true adsorption, or as a chemical reaction in which a simple combination

between the hydroxide as a whole, and some of the mineral constituents of the soil takes place. The experimental facts have an obvious bearing on the question of the liming of soils to reduce acidity, and on the reliability of lime requirement methods for estimating soil acidity.

(d) *Molecules* of certain substances are apparently adsorbed by colloidal particles of soils under certain conditions. The removal of dye-stuffs from their solutions has been suggested as a means of determining the quantity of colloidal matter in soils. It is difficult to discriminate in all cases between the adsorption of whole molecules and the simultaneous adsorption of ions produced by their dissociation. The subject need not be further discussed, except to point out that selective adsorption is exhibited by the colloidal substances in soils towards the molecules of specific compounds.

5. THE MEASUREMENT OF SOIL ACIDITY: LIME REQUIREMENTS OF SOILS.

The following tabular arrangement [79] includes the chief methods that have been suggested for the estimation of soil acidity.

(a) *Methods of estimating soil acidity.*

I. A neutral salt solution is added to the soil.

The following salts amongst others have been used. Sodium chloride (Hopkins, 1903); calcium acetate (C. H. Jones, 1913); potassium acetate (Oscar Loew, 1913); potassium chloride (Daikahura, 1914).

II. Pure water is added to the soil.

(A) The mixture is titrated with *lime water* (Veitch, 1904. Bouyoucos, 1916), or a solution of *calcium bicarbonate* (Hutchinson and McLennan, 1914), using either an indicator or observation of the freezing point to determine the end point. This gives the amount of lime needed to neutralize the acid originally present in the soil, plus that produced by the indirect action of the calcium compound added, as well as the amount of lime required to satisfy the adsorptive power of the soil colloidal substances for calcium-ion under the given conditions. In this sense they are therefore *lime requirement* methods.

(B) The mixture of soil and water is filtered, and the acid in the filtrate estimated by titration with standard alkali. This determination gives the *total quantity* of acid extracted from the soil by the water treatment.

(C) The *hydrogen-ion concentration* of the mixture of soil and water, or of the centrifuged or filtered extract is determined.—

(a) By catalysis of an ester such as ethyl acetate, (Conner, 1916).

(b) By catalysis of sucrose (Rice and Osugi, 1918)

(c) By measurement of the electric potential due to hydrogen-ion by using the potentiometer (Gillespie, 1916).

By observations of colour changes of indicators whose relations to hydrogen-ion concentration are known (Gillispie 1916).

(b) *Notes on the methods used for estimating soil acidity.*

1. The methods outlined under heading I in the foregoing table are clearly not methods of determining the acidity originally present in a soil, since the results given by them are composite. in that they represent both the acid originally present, and a usually greater quantity produced by the treatment with the salt solution. Actual trial has shown that the results obtained vary with the kind of salt used, and with the conditions of the experiment [3]. In certain cases neutral or slightly alkaline soils may develop considerable acidity, when treated with a salt solution [6 9] as has been explained in previous sections. Hence the methods are of little value when employed in investigations into the effect of soil acidity on plant growth.

2. The methods outlined under the heading IIA include the most commonly used *lime requirement* methods. They undoubtedly give a correct indication of the amount of lime needed to bring a soil to the degree of alkalinity shown by the indicator used, and if the freezing point method of determining the end point is employed (Bouyoucos, [5]), it may be possible to recognize the point at which the soil acids are just neutralized, as well as that at which lime ceases to be taken up by the soil. In this way the latter method is perhaps capable of yielding results representing both total quantity of acid and lime-requirement (see summary of Bouyoucos' results,[7 8] p. 337).

3. The method outlined in IIB enables one to determine the *total quantity* of acid in a soil in the most direct and simple way. The indicator used must, however, show the correct point of neutralization as defined upon physico-chemical grounds (i.e pH = 7·0). Neither methyl orange (range pH 3·1 to 4·4) nor phenolphthalein (range pH 8·3 to 10·0) can be used. Bromthymol blue (range pH 6·0 to 7·8) would give the most satisfactory results.

4. Methods based on the estimation of the hydrogen-ion concentration of the soil extract (IIC) are of the most value in researches into the relation between soil acidity and plant growth, for it is not the *total quantity* of acid which is locked up, as it were, in the difficultly soluble alumino-silicic acids, the humus and the other acid-yielding constituents of soils, that is of importance in regulating the processes that go on in soils, but the *intensity of acidity* of the soil-solution. Recognition of this fact has given prominence to the methods of estimating soil acidity last mentioned, and these methods have largely replaced the older lime-requirement methods in researches in soil science.

(C) *Methods of measuring the hydrogen-ion concentration of soils.*

Of the four methods indicated in the table (namely IIC, a, b, c and d), the last two only are in general use in soil researches. They may be referred to as the hydrogen electrode method and the colorimetric method, respectively. The former gives more accurate results than the latter, but it is more difficult to manipulate, and necessitates the use of costly apparatus. It forms the basis, however, of all accurate determinations of hydrogen-ion concentration, not only in soil science, but also in physiology and bacteriology.

It is not intended here to give a detailed account of the hydrogen electrode method, as this would necessitate too deep an incursion into the fundamental facts of physical chemistry. The reader is referred to a recent book by Dr. W. Mansfield Clark [11] for a full discussion of the theoretical and practical aspects of this subject.

The colorimetric method will be briefly described, however, for it is the method which is universally used in rapid soil surveys as carried out in modern investigations.

The colorimetric method of determining hydrogen-ion concentration is based upon the fact, that there exists for each of certain complex organic compounds called indicators, a characteristic zone of hydrogen-ion concentration within which its colour changes take place. Phenolphthalein, for instance, is colourless in solutions of hydrogen-ion concentration greater than that represented by a pH value of 8·3. If the solution is slightly more alkaline (i.e. its pH value is numerically greater than 8·3), a pink colour appears and gradually becomes more intense with increasing alkalinity, until the indicator appears to give its full colour at about pH = 10. Methyl orange, which is yellow in alkaline, neutral and slightly acid solutions, exhibits its intermediate colours between pH = 3·1 and pH = 4·4. These two well-known indicators are not altogether suitable for colorimetric work however, either because the colour change is not sufficiently sharply defined, or because the pH range is too small.

Several new and very brilliant indicators have recently been prepared and placed on the market. The pH range of each has been accurately determined by the use of carefully made solutions whose exact pH values were checked by the hydrogen electrode. [12]. The set of seven indicators described below, which together cover a pH range of 3 to 10, are generally used in the examination of soils. A special technique has been elaborated, and this enables the soil chemist to estimate with a sufficient degree of accuracy, and in the minimum of time, the intensity of acidity exhibited by any given soil sample. The technique is fully described by its inventor in a recent paper [26] to which reference must be made for full details A short abstract is given below in order to indicate the principle of the method.

It is unnecessary here fully to discuss the theory of indicators, since the colorimetric method, after all, is simply a comparative method based on absolute measurements of hydrogen-ion concentration with the hydrogen electrode; it therefore entails no knowledge of the nature or seat of the colour changes of the indicators employed. The reader is

referred to Prideaux[58] for an exhaustive discussion of the theory of indicators.

The following brief review will serve as an introduction to the description of the actual colorimetric method as applied to soils. Let us assume that indicators are acids or bases whose undissociated molecules have a different colour from that of their dissociated products. For example, let us consider phenol red to be an acid of type HA, and that the undissociated molecules HA, are yellow in colour, whilst its acid radicle-ions, A, are red. When phenol red is dissolved in a certain volume of pure water at ordinary temperature, it will dissociate according to the equation $HA \rightleftharpoons H' + A'$, and equilibrium will be attained between the undissociated molecules and the ions liberated, so that $\frac{[H'] \times [A']}{[HA]} =$ a constant.

(The square brackets signify the concentration in grams per litre of the ions or molecules). The constant is known as the *dissociation constant* of the substance at the specified temperature and for the degree of dilution of the solution.

There will therefore exist, in the case of a solution of phenol red, a certain number of yellow-coloured molecules of the undissociated compound, and a certain number of acid-radicle ions (A′) of a red colour, together with an equal number of colourless hydrogen ions (H). The resulting colour of the solution will lie somewhere between yellow and red, and its exact shade will depend on the relative number of HA and A′ present.

Suppose now we increase the concentration of hydrogen-ion, by adding a few drops of some acid. The result of this will be to suppress the dissociation of the indicator, and thus to increase the number of yellow-coloured undissociated molecules. Hence the solution will assume a more yellow shade of colour. For every intermediate shade between red and yellow there will therefore be a corresponding hydrogen-ion concentration or pH value, and if we possess previous knowledge of the correlation between pH value and shade of colour, we shall be able to estimate the hydrogen-ion concentration in any given solution, provided that the range of the indicator used includes the pH value of that solution.

The simplest way of standardizing the shades of colour given by an indicator, is to employ a colour chart in which various shades of colour are reproduced with the corresponding pH value stated for each. Such a chart is published for the seven indicators usually employed in colorimetric work, at page 40 of Clark's book already mentioned[11]. Separate copies can be obtained of this colour chart. By its use a rough estimation of the hydrogen-ion concentration of a soil solution can be made, the degree of accuracy being within about 0·4 of the correct pH value. Quite recently, the La Motte Chemical Products Company, of Baltimore, have advertised an inexpensive set of seven indicators, made up into solutions of convenient strength, and contained in tubes fitting into a small box that can be taken into the field. Instructions are provided showing how approximate pH determinations can be made on the spot.

The method of Gillespie,[26] now to be described, gives results of a greater degree of accuracy than that in which a colour chart is used. The colour standards in Gillespie's method are obtained without the use of standardized solutions, in the following way. Two parallel rows of nine narrow uniform test tubes are arranged in a rack. Into each, 10 c.c. of water are placed. The indicator solution to be used is then added in drops to each tube, the number of drops varying uniformly from 1 to 9 in the first row, and 9 to 1 in the second, as indicated in the diagram. The full acid colour is then developed in the indicator solutions in the first row of tubes, by adding a small quantity of acid to each, and the full alkaline colour is similarly developed in the second row, by means of dilute alkali. If any adjacent pair of tubes, one from each row, is taken and viewed by light transmitted through both tubes, the shade of colour observed will depend on the drop ratio of the indicator present. For each drop ratio, and for each of seven indicators, the corresponding pH value has been determined, and the results drawn up in a table which is reproduced at page 126 of Gillespie's paper above mentioned.

	Number of drops of indicator in each tube.								
Full alkaline colour	1	2	3	4	5	6	7	8	9
Full acid colour ...	9	8	7	6	5	4	3	2	1
Drop ratio .. .	1:9	2:8	3:7	4:6	5:5	6:4	7:3	8:2	91
Colour of paired tubes	yellow	yellow green		green		blue	e-green		blue
Brom-thymol blue pH value corresponding to the drop ratios when *brom-thymol blue* is used	6·15	6·5	6·7	6·9	7·1	7·3	7·5	7·7	8·05

The names and pH ranges of the seven indicators most commonly used are as follows :—

Name.	Acid colour.	Alkaline colour.	pH range.
1. Brom-phenol blue ...	yellow	purple-blue	3·0 to 4·6
2. Methyl red	red	yellow	4·4 to 6·0
3. Brom-cresol purple	buff	purple	5·4 to 7·0
4. Brom-thymol blue	yellow	blue	6·0 to 7·8
5. Phenol red	yellow	red	6·8 to 8·4
6. Cresol red	yellow	purple-red	7·2 to 8·8
7. Thymol blue ...	buff	deep blue	8·2 to 9·8

In soil work, 15 grams of the soil sample are mixed in a flask with 30 c.c. of pure water whose reaction as ascertained in a previous trial is neutral (pH = 7·0). The mixture is shaken for some time and then allowed to stand, preferably overnight. It is then centrifuged or filtered,* using the filter-pump if necessary. 10 c.c. of the clear extract are placed in a tube of the same size as those used for the colour standards, and 10 drops of the indicator solution are added. The colour developed is now compared with various pairs of tubes which form the colour standards, the tubes being held in a comparator. When the correct match has been obtained, reference is made to the table of drop ratios which gives the corresponding pH values, and thus the pH value of the soil extract is determined. The results have been found not to differ much from those obtained with the soil solution itself, as expressed from soil by the use of powerful compressors or oil pumps, [28], [57], [69].

BUFFER ACTION IN SOILS.

In order to understand what is meant by the term *buffer*, it would be advisable to consider first a simple example. Suppose a few drops of hydrochloric acid are added to a solution of sodium acetate. Both of these compounds are highly ionized in solution, but when mixed, opportunity is given for the formation, by their interaction, of two other compounds, namely sodium chloride and acetic acid, the former of which is highly ionzied, but the latter very feebly so. Hence in the mixture, the hydrogen-ions and the acetate-ions, produced by the dissociation of the hydrochloric acid and the sodium acetate, respectively, will unite almost completely to form acetic acid, and as a consequence the hydrogen-ions will very nearly disappear.

The reactions may be expressed thus :—

$$HCl \rightleftharpoons H^{\cdot} + Cl'$$

$$CH_3COONa \rightleftharpoons Na^{\cdot} + CH_3{\cdot}COO'$$

$$H^{\cdot} + CH_3{\cdot}COO' \rightleftharpoons CH_3{\cdot}COOH \text{ (feebly ionized).}$$

The effect of sodium acetate on the ionization of hydrochloric acid is therefore to bring about a considerable reduction in its hydrogen-ion concentration, and for this reason sodium acetate is spoken of as a *buffer*.

There are many compounds or mixtures of compounds known which can act as buffers in a similar way. Their presence in such liquids as plant-sap, blood and sea-water confer on these liquids the important property of being able to resist change in reaction by virtue of their ability to soak up, as it were, excess of hydrogen-ions which may in some way or other gain access to the liquids.

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* Centrifuging is preferable to filtration because the use of filter-paper may produce an alteration in pH value by the paper adsorbing certain ions from the soil extract.

Furthermore, certain subtances are capable of functioning as buffers both against change in acidity and change in alkalinity; that is they are able to remove hydroxyl-ions as well as hydrogen-ions when these occur in excess in a solution. They are themselves so constituted that they can function both as bases and as acids depending upon external conditions, which in some way decide the kiud of ionization that their molecules undergo. Examples of such substances are the simple amino-acids and the proteins. Water itself, from what has been stated about its dissociation, is also an example. They are called *amphoteric substances* or *ampholytes*, and their presence in liquids, such as those mentioned above, is of great physiological importance in that they regulate the reaction of these liquids by maintaining a constant hydrogen-ion concentration by reason of of their buffer properties.

Recently, convincing evidence has accumulated which indicates that soil solutions contain certain compounds that are able to function as buffers. The explanation by Henderson in 1909* of the mechanism of the buffer action in blood as being chiefly due to the presence of carbonates and phosphates in solution, naturally points to these compounds as the probable seat of buffer action in the soil solution. Examples of soils containing appreciable amounts of carbonate and yet possessing both considerable lime requirements, as determined by certain conventional methods, and giving an acid reaction with indicators, have frequently come to the notice of soil investigators. This apparent anomaly in connexion with West Indian soils has been commented upon by Watts [7 8]. An explanation of the phenomenon would perhaps therefore be welcomed.

(a). *The bicarbonate buffer system in soils.*

Calcium carbonate ($CaCO_3$) is almost insoluble in pure water, the extent of its solubility being of the order of 1 part in 100,000 at ordinary temperatures[5 8]. In the soil, and indeed under any other conditions in which the compound occurs in nature, calcium carbonate is exposed to the action of carbon dioxide, for both the sub-aerial and the soil-atmosphere contain the gas in varying proportions. The soil solution in contact with carbon dioxide dissolves a certain amount of the gas until a state of equilibrium is reached between the dissolved compound and that which is still in the free state in the gaseous environment. The concentration of the saturated solution is proportional to the pressure of the carbon dioxide in the environment, and thus depends on the percentage amount of the gas in the soil atmosphere.

In solution, carbon dioxide reacts in part with water to form carbonic acid which is feebly ionized into hydrogen-ions and bicarbonate-ions ($HCO_3$1). The following equations illustrate the relationships between the different molecules and ions in the system carbon dioxide and water :—

$$CO_2 \text{ (gas)} \rightleftarrows CO_2 \text{ (dissolved)} + H_2O \rightleftarrows H_2CO_3 \rightleftarrows H' + HCO_3$$

*For a clear account of buffer action as exhibited by the fluids of the animal body, the reader is referred to 'Principles of General Physiology,' by W. M. Bayliss, London : *Longmans Green*, 1920, 2nd Edition, 25*s*.

When calcium carbonate is in contact with water containing carbonic acid, the small amount of carbonate which first of all dissolves in the pure water is partly ionized into calcium-ions and carbonate-ions (CO_3''). The calcium ions combine with the HCO_3-ions produced by the dissociation of the carbonic acid in the solution, and calcium bicarbonate molecules ($Ca(HCO_3)_2$) are formed. Similarly, the carbonate-ions combine with the hydrogen-ions of the acid to produce more HCO_3-ions which also enter into the formation of more bicarbonate. The equations which represent these various reactions are :—

(i) $Ca\,CO_3 \rightleftharpoons Ca^{\cdot\cdot} + CO_3''$.

(ii) $H_2\,CO_3 \rightleftharpoons 2H^{\cdot} + HCO_3'$

(iii) $CO_3'' + H^{\cdot} \rightleftharpoons HCO_3'$

(iv) $Ca^{\cdot\cdot} + 2\,HCO_3' \rightleftharpoons Ca(HCO_3)_2$ (unionized).

The ultimate result of the exposure of calcium carbonate in contact with the soil solution to the action of carbon dioxide contained in the gaseous environment is thus seen to be the formation of soluble calcium bicarbonate through a series of closely interrelated reactions which are controlled each by its special ionic equilibrium factors. The solid calcium carbonate slowly disappears as such, and enters into solution in the soil water as the bicarbonate. Provided that calcium carbonate is in sufficient excess in the soil, equilibrium is attained for any given proportion of carbon dioxide in the gaseous environment between free carbon dioxide ; dissolved carbon dioxide ; carbon dioxide ; carbonic acid in solution ; solid calcium carbonate, and dissolved calcium bicarbonate.

Calcium bicarbonate is a very soluble compound. It is also ionized in solution to the extent of about 85 per cent. into ions of calcium and of bicarbonate (HCO_3'). Further, it has been proved that a solution of calcium bicarbonate possesses an alkaline reaction towards indicators by reason of the slight increase in hydroxyl-ion concentration which it produces when dissolved in water, due to the hydrolysis of bicarbonate-ions, thus—

(v) $HCO_3' + H_2O \rightleftharpoons H_2CO_3 + OH'$.

Let us now consider the effect of gradually increasing the percentage of carbon dioxide in the gaseous environment of a soil containing calcium carbonate in contact with the soil solution in which dissolved calcium bicarbonate is present in equilibrium with the other units of the system. First, more carbon dioxide dissolves, and this causes an increase in the amount of carbonic acid already present. This in turn brings about an increase in hydrogen-ion concentration sufficient to suppress the concentration of hydroxyl-ion due to hydrolysis as indicated by equation (v) above, and thus to reduce the alkalinity of the solution, until eventually such a proportion of carbon dioxide in the gaseous environment is reached to give the soil solution a neutral reaction.

Suppose that when this stage of neutrality in the bicarbonate-carbon dioxide system has been attained, an additional number of hydrogen-ions are introduced into the system by the addition of a small amount of some acid. The immediate effect

of this will be to lower the concentration of HCO_3' by combining with these ions to form molecules of the feebly-ionized carbonic acid. The latter compound will in part decompose into carbon dioxide and water, and some carbon dioxide will escape into the gaseous environment, until equilibrium in the whole system has been restored. The added hydrogen-ions are therefore soaked up, as it were, and do not appreciably alter the acidity of the soil solution. The bicarbonate—carbon-dioxide system is thus comparable with the sodium—acetate-acetic acid system already described, and the bicarbonate herein acts as a buffer in maintaining the hydrogen-ion concentration of the soil solution at a nearly constant value.

In a similar manner, the addition of a small amount of alkali to the bicarbonate– carbon-dioxide system brings about no appreciable change in reaction, because the extra hydroxyl-ions introduced reverse the hydrolytic action expressed by the equation. $HCO_3' + H_2O \rightleftarrows H_2CO_3 + OH'$, and the increase in HCO_3' concentration is balanced by the formation of more calcium bicarbonate molecules by suppressing the dissociation of this compound.

It is therefore possible for a soil to contain an appreciable amount of bicarbonate and carbonate and yet to possess a soil solution exhibiting a degree of hydrogen-ion concentration above that represented by neutrality, for the various acidic compounds in an acid soil may yield hydrogen-ions in sufficient number to bring about an accumulation of excess of these ions in spite of the buffering effect of the carbonates in the system in equilibrium. It is the bicarbonate and the carbonate found up as it were in this system that are detected when an acid soil is subjected to chemical analysis in estimating its carbonate content.

(*b*) *The phosphate buffer system in soils.*

The presence of phosphates in the soil solution, just as in the case of blood, etc., may also cause a buffering effect, for, by considerations similar to those brought forward in explaining the buffer action of the bicarbonate system, it can be shown that a solution containing monosodium phosphate (NaH_2PO_4) and di-sodium phosphate (Na_2HPO_4) can possess a degree of hydrogen-ion concentration which is altered but slightly by the addition of small amounts of acid or alkali.

(*c*) *Other buffer systems; the effect of soil organic matter.*

It may be stated as a generalization following upon the facts already outlined, that all salts of strong bases (such as potassium sodium and calcium), and weak acids (such as carbonic, phosphoric, and boric acid, and most organic acids) can act as buffers because they yield hydrogen-ions by hydrolysis when placed in water. Further it can be shown that salts of weak bases and strong acids also possess buffer properties in solution. The common factor that makes buffer action possible in all these cases is the slight electrolytic dissociation which weak acids and weak bases exhibit in solution.

Amphoteric compounds owe their buffer properties to the fact that they can act either as weak acids or as weak bases under different conditions. The importance of proteins as amphoteric buffers in physiological liquids, such as plant saps, animal tissue juices and bacterial culture media, has frequently been pointed out in recent work, and their importance in soils is now also being recognized as furnishing an explanation of certain of the distinctive properties shown by soils rich in organic matter.

Thus Stephenson [74], basing his arguments on the chemical constitution of the proteins and their decomposition products, maintains that organic matter in soils is not likely to produce acidity, except when anaerobic conditions due to water-logging prevail, but will rather tend to prevent an increase in acidity due to other causes. He also showed [73] by pot experiments, that dressings of highly nitrogenous organic compounds have the effect of decreasing soil acidity. Coville [16] has stated that decomposing leaf-mould liberates acids, but Noyes and Yoder [51] hold that such acidity is due chiefly to carbonic acid weakly held by the organic matter. On the whole, it seems fairly well established that organic matter in normal well-drained soils tends to regulate the reaction of the soil solution by buffer action, and thus to prevent excessive concentration of hydrogen-ions rather than to augment it.

(B). THE RELATION OF TRUE SOIL ACIDITY TO PLANT GROWTH.

It is usually maintained by practical agronomists that soil acidity is harmful to most cultivated plants, and that for a soil to exhibit maximum productivity, it should contain a sufficient amount of lime to give a neutral or alkaline reaction. These beliefs are reflected in the adage that 'a limestone country is a rich country', and in a statement by the late Director of the Rothamsted Station that any soil containing less than 1 per cent. of calcium carbonate will benefit by liming.* If instead of the term *acidity* we substitute *sourness*, as defined and discusssed in the introductory to this paper, the above initial statement becomes admissible.

When acidity is considered in its physico-chemical sense, it can be shown that soil acidity, if unaccompanied by other inhibiting factors, is not *per se* ordinarily the limiting factor to plant growth in sour soils. The common occurrence of fertile soils exhibiting acidic reactions towards indicators, and therefore containing in their soil solutions a concentration of hydrogen-ions greater than that possessed by pure water, has been pointed out by numerous investigators, for example, Gillespie [24], Hoagland and Sharp [35] and Plummer [57]. Hoagland has described [36] several Californian soils which although giving pH values varying from 4·5 to 6·0, support very good crops of barley, oats, beans, potatoes, corn, etc. Moreover these soils were found to produce nitrates at a rapid rate, so that bacterial activity was by no means lacking in them.

1. THE EFFECT OF ACIDITY ON THE GROWTH OF SEEDLINGS AND ON THE GERMINATION OF SEEDS.

Recent work has shown that many agricultural plants can grow successfully in nutrient solutions possessing a considerable

*Hall, A. D. 'Fertilizers and Manures' London. John Murray: 1st Edition, 1909, p. 253.

degree of acidity. Thus Hoagland [35] grew barley seedlings in nutrient solutions of pH value 5·0, and found that the acid reaction was in no way injurious to the plants. Similarly Breazeale and Le Clerc [6] found that wheat seedlings were unaffected by a degree of acidity much higher than that exhibited by many sour soils. Still more recently, Salter and McIlvaine [66] have established the optimum reaction which favours the growth of seedlings of wheat, soy bean and alfalfa. They found this to be a reaction expressed by pH 5·94 in their experiments with nutrient solutions. For maize, the optimum pH value was similarly found to be 5·16. The limits of hydrogen-ion concentration within which seed germination could proceed were fixed at the pH values 2·96 and 7·71, so that a slightly acid reaction was found most favourable to germination in all the species examined. Certain other investigations, however, have yielded results somewhat conflictory to those recorded above. Thus Von Brehmer found that lime increases the germinating capacity of the seeds of a number of Phanerograms, and Claudell and Crochetell that an acid reaction is injurious to germinating seeds. Similar results were obtained by Tolf. (See Salisbury, 65 p. 215.) It would appear therefore that the beneficial or injurious effect of acidity on the germination of seeds varies with the species of plant which produces those seeds.

On the whole the facts indicate that the physiological processes that go on in soil and plant, and which find their final expression in the absorption by the plant roots of various ions that are essential for nourishment, are markedly modified by the presence of an excess of hydrogen-ion.

The influence exerted by hydrogen-ion in this connection would thus appear to be one phase of the vast question of the physiological balance in the nutrient solution of the different ions absorbed by plants, such balance being essential to the production of optimum growth. A great deal of research work has been performed in this domain, and the facts so far discovered are so numerous and difficult to correlate that a general discussion of the subject would be impossible in this paper. The main features of the question of physiological balance of the soil solution and the effect of manures on it will possibly be outlined in another paper shortly to appear in this journal. It may be relevant to our subject, however, to state a generalization recorded by Hoagland [37] that, in solutions of an acid reaction represented by a pH value of 5·0 to 5·5, the absorption by plant roots of various ions, notably ions of calcium, nitrate-ions and phosphate-ions, is greater than in approximately neutral solutions (pH 6·8) of similar composition and of the same total concentration.

This conclusion is somewhat discountenanced by the results of plant nutrition studies carried out at the Maryland Experiment Station, where McCall and Haag [47] have recently shown that the observed variation in plant growth with the different types of nutrient solutions used could not be definitely correlated with differences in the hydrogen-ion concentrations of the

solutions. A great deal of research work is nowadays being performed on the physiological aspects of plant growth and its relation to the composition and concentration of the soil or nutrient solution. Doubtless the true significance of the hydrogen-ion in these relationships will in due course be finally established.

2. THE EFFECT OF ACIDITY ONTHE BENEFICIAL MICRO-ORGANISMS IN THE SOIL.

It is well known that the majority of the processes that are connected with the decomposition of plant residues in the soil, including those that are especially concerned in the nitrogen-cycle, are controlled by the activities of micro-organisms, many species of which have been isolated and described. Whereas little is yet known of the life histories and mode of action of most soil micro-organisms, certain of the bacterial species that control nitrification (e.g. Nitrosomonas, Nitrobacter) and nitrogen-fixation both by free-living forms (e g Azotobacter, Clostridium) and by symbiotic forms which produce nodules on the roots of leguminous plants, (e.g. Pseudomonas, Rhizobium), have been the objects of detailed study. The formation of ammonium compounds (ammonification) from the complex nitrogenous organic compounds present in plant residues, is governed by numerous species both of fungi and of bacteria, each of which controls one stage of the decomposition Only a limited number of these specific organisms have been so far described, but studies of the fungi and bacteria of ammonification, considered as a whole have yielded some information as to the conditions governing their activities.

Detailed investigations of the effect of the reaction of the medium on the activities of certain of the micro-organisms concerned in the main processes of the nitrogen-cycle in the soil, as outlined above, have been made, chiefly in nutrient solutions. We may describe the findings of these investigations in separate sections.

(a). Numerous workers have observed that *ammonification* is prevalent in soils of all kinds, and that acidity seems to have no particularly adverse effect upon the life of the micro-organisms that are responisble for it

Thus Coville [15] has shown that many soils acid to litmus contain large amounts of ammonium compounds. Fred and Graul [20] have also shown that the formation of ammonium compounds from casein takes place so rapidly in an acid soil that for several weeks after the nitrogenous substance is added, the production of nitrates is not limited by lack of ammonium compounds. Kopeloff [13] has dealt with the part played by certain soil fungi in ammonification. and has reviewed the literature of this branch of the subject. His own researches show that ammonifying fungi can withstand a much greater intensity of acidity than can ammonifying bacteria, and that in acid soils, these fungi may be instrumental in maintaining the rate of production of ammonium compounds in the soils.

(b). With *nitrification* the case is somewhat different from the last. In his classical researches on the nitrification process in soils, Warington came to the conclusion that the presence of a base with which nitric acid formed in the process can combine is a necessary condition. Dehérain [18] in 1894 stated that 'the nitric ferment does not act in an acid medium,' but he also noted that nitrification may go on in a soil deficient in lime. As long ago as 1872, Houzeau [34] reported nitrification in an acid soil. In 1908, Hall, Miller and Gimingham [30] found nitrates in a soil of marked acid reaction, but they considered that the presence of small isolated particles of calcium carbonate made possible the activity of nitrifying bacteria in the immediate vicinity of these particles. Since then many other workers have recorded nitrification in acid soils.

(c). *Nitrogen-fixation* by free-living bacteria. Christiansen, in Denmark, has investigated the prevalence of *Azotobacter* in soils of varying degrees of acidity. He found that this organism was especially sensitive to the presence or absence of lime in the soil, and proposed using *Azotobacter* as an indicator for giving information as to the lime requirements of soils. Christiansen has compared [10] the *Azotobacter* test with the litmus test for soil acidity, and with the commonly used lime-requirement methods. He noted a close correlation between intensity of acidity, as gauged roughly with litmus, and the presence or or absence of *Azotobacter*.

Bear [4] has summarized the literature on the subject up to 1917, and presents the results of his own experiments in which he has verified many of the facts above mentioned. Bear found that the several types of soil organisms known to be beneficial to plant growth vary in their response to liming. Ammonification apparently proceeds in almost any soil whether deficient in lime or not; nitrification proceeds best in soils that are not deficient in lime; nitrogen-fixation by non-symbiotic organisms, such as *Azotobacter*, is markedly increased by increase in the lime content of a soil.

In the investigations outlined, comparisons have been chiefly made between micro-organic activity in soils and lime requirement. No very exact data as to the *intensity* of acidity in the soil or culture solutions used in these researches are presented. Gainey, however, in 1918 [23] attempted to correlate the activity of *Azotobacter* in soils with the hydrogen-ion concentration of the soil solutions. He used indicators to obtain the pH values for the soils examined. His results show that there is good reason to believe that *Azotobacter* will not thrive well in soils whose acidity is greater than that represented by the pH value 6·0.

(d). That bacteria which are able to fix atmospheric nitrogen when living in symbiosis with certain leguminous plants are markedly affected by the reaction of the medium in which these plants grow, has also been demonstrated in a limited number of investigations. An historical review of these researches is given in a paper by Fred and Davenport [19]. Beijerinck in 1888 showed that *Rhizobium leguminosarum* is injured in a medium of minimum acidity equivalent to an acidity of N/50 concentration. Numerous other workers have since made somewhat conflictory

statements, but much of the earlier work requires revision in view of recent researches on the effect of hydrogen-ion concentration on bacterial processes as contrasted with that of total acid. Fred and Davenport (*loc. cit.*) worked with pure strains of *Rhizobium leguminosarum* obtained from different leguminous plants, and found that the critical pH value for each of these strains varies considerably. Thus for lucerne (alfalfa) and sweet clover, the critical pH value was found to be 4·9; for peas and vetch, 4·7; for red clover and common beans, 4·2; for soya beans and velvet beans, 3·3, and for lupins 3·15. Each of these plants is apparently able to thrive in soils of varying degrees of acidity by reason of the adaptability of their special strains of nodule bacterium to the reaction of the soil solution.

Although many investigations, such as these outlined above, have been carried out with bacterial cultures in nutrient media, as yet these studies have not been supplemented by actual observations in the field. It seems quite possible that certain acid-resisting bacterial strains may exist in soils. Indications of their activity have been noted in culture studies, and their presence in certain soils of extreme acidity must be postulated if one is to explain the nitrogen transformations which go on in such soils.

3. THE EFFECT OF ACIDITY ON PLANT DISEASE ORGANISMS.

The relation between the intensity of acidity of the medium and the life of beneficial soil organisms, as described in the last section, may be extended to include other soil organisms of pathogenic importance. Bacteriologists and mycologists have long been aware of the dependence of living cells on the maintenance of a limited, and in many cases of a very strictly limited, hydrogen-ion concentration in the environment, and have used this knowledge in studies on the life-histories and methods for the control of organisms responsible for certain animal and plant diseases.*

Farmers in temperate countries have suffered for many years the scourges of an organism which is prevalent in soils lacking lime and which produces a disease known as 'finger and toe' in cruciferous crops, such as turnips and cabbages. Voelcker in England showed in 1859 that liming, by correcting the acidity of infected soils, brought about a surpression of this disease. Another disease of common occurrence in temperate countries, and dependent for its incidence and spread on an acid soil condition, is the scab of potatoes. Recently the existence of a definite limit of acidity has been demonstrated for this organism by Gillespie [25], who worked in the laboratory with cultures of the organism. Studies of the field conditions in relation to potato scab were also undertaken by Gillespie and Hurst [26], who showed that the scab organism does not thrive well in soil whose soil solution is more acid than an intensity represented by pH 5·2. As a corollary to this discovery, Martin [15, 16] showed that potato soils with alkaline reactions and

* For a summary of literature and references see (11) p.p. 220-23, and (12) pp. (1-11).

growing scabby tubers could be corrected by the application of suitable dressings of sulphur. The oxidation of this substance in soil, under the control of certain sulphur bacteria, gives rise to sulphuric acid, which neutralizes the excess of lime in the soil, and leaves it with an acid reaction.

Exactly how far studies similar to the above on the relation between soil reaction and the spread of other plant diseases may yield important results, yet remains to be seen, for doubtless many other investigations in this branch of soil science will be attempted in the near future.

III. DEFICIENCY IN CALCIUM COMPOUNDS AS A FACTOR IN SOIL SOURNESS.

That the most general characteristics of sour soils is their deficiency in easily soluble base has already been noted in the Introductory. This deficiency of base is responsible for the accumulation in the soil solution of an excess of hydrogen-ion produced by the dissociation of acidic substances present in sour soils. When a base such as calcium carbonate is added to these soils in sufficient amount to disturb the equilibrium of the bicarbonate-carbon-dioxide system, as described in the section on buffer action, it completely suppresses the excess of hydrogen-ion by yielding an increasing supply of hydroxyl-ions.

The extent to which the infertility of sour soils is due to the actual presence of excess of hydrogen-ion rather than to the absence of a necessary concentration of calcium-ion in the soil solution, other inhibitory factors being absent, has only recently been studied in detail. The facts presented in the last section indicate that the most desirable reaction of the soil solution, in so far as the nutrition of the plant is concerned, is probably one of marked acidity, corresponding to a pH value lying between 5·0 and 6·0. The proper development of the nitrogen-transforming organisms occurring in soils, however, apparently requires an optimum reaction considerably less acid than this, so that in actual agricultural practice a compromise has to be allowed, unless an attempt is being made to combat some disease located in the soil by impressing some definite reaction upon the soil solution.

Besides influencing the reaction of the soil solution, calcium carbonate in soils exerts a marked influence on the texture, for it gives rise to the soluble bicarbonate which flocculates colloidal clay. This subject, which belongs to the domain of soil physics, need not be discussed here.

1. THE ROLE OF CALCIUM IN PLANTS.

That calcium compounds are required by plants in considerable amounts is indicated by analyses of plant dry matter. Parker and Truog [55] recorded the compositions of thirty-four species of plants with respect to certain elements, and concluded that there exists a close relationship between the calcium and the nitrogen content of these plants. Members of the Gramineae were observed to possess a relatively low calcium-nitrogen ratio

(average figure 0·306 per cent.). These plants are known in the field to possess considerable tolerance to soil-acidity. Leguminous plants and other species which generally respond markedly to liming, and are sensitive to acidity, were observed to possess higher calcium-nitrogen ratios (average figure 0·553 per cent.). These results are taken to indicate some undetermined difference in the metabolic processes of the two groups of plants.

Calcium compounds are needed by plants for at least two purposes: (1) to furnish the comparatively small amounts of calcium necessary to the plant in the synthesis of proteins and other plant substances, and (2) to neutralize and precipitate acid substances that are present in the plant sap, and which are manufactured as by-products of katabolism. Thus the oxidation of proteins gives rise, amongst other products, to organic acids, of which formic, acetic, oxalic, succinic, malic, and caprionic are the chief. Plants high in proteins would therefore be expected to produce large amounts of waste acids products, and consequently to show high lime requirements. This may explain the large calcium content of leguminous plants, etc., which contain an exceptional amount of protein nitrogen [55].

Any kind of soluble calcium salt in a soil would apparently serve to supply the direct nutritive needs of a plant, but the second purpose would seem at first sight to require that the calcium compound should be the bicarbonate alone. Calcium bicarbonate, being a very soluble salt, and possessing a high degree of dissociation in solution, is able to yield a considerable concentration of calcium-ion and of bicarbonate-ion (HCO'_3) to the soil solution. It may be assumed that plant roots are able rapidly to absorb both calcium-ions and bicarbonate-ions from the soil solution. The calcium-ions, besides playing other important rôles in plant metabolism, may precipitate in the plant sap certain acid ions, such as the oxalate-ion, because they form molecules of insoluble compounds with them. The bicarbonate-ions, on the other hand, may suppress the concentration of hydrogen-ion due to the dissociation of acidic waste products in the sap. Carbonic acid would be formed; this in part decomposes, giving carbon dioxide, which might escape into the intercellular spaces and be excreted by the plant. In this way calcium bicarbonate may be able to precipitate and to neutralize the acidic waste products formed during metabolism. In view of the fact that many plants will grow in media of definite and appreciable acidity, it would appear that there is some flaw in the theory as propounded above, and that there is no need to postulate that plants must absorb both calcium-ions and bicarbonate-ions in order to maintain a constant and inexcessive degree of hydrogen-ion concentration in their sap. It is quite possible that the only essential factor in the case is that a sufficient number of calcium-ions should be available in the plant sap to lower the degree of dissociation of the acid waste-products by forming with the acid-ions calcium compounds of low ionization constants, or of low solubility. In this way the calcium-ion alone may conceivably be capable of reducing the acidity of plant sap and preventing the accumulation of harmful acid waste-products.

The whole question of the rôle of calcium in the complex processes that go on within the plant body is somewhat difficult

to understand ; it need not be more fully discussed in this place The fact remains clear that plants require a considerable supply of calcium over and above that which enters into the composition of the body substances.

Truog [75] sums up the situation by stating that different plants have different lime requirements which refer to the 'actual lime needs of the plant itself, especially as to the use and rate at which lime must be secured from the soil by the plant for normal growth' (*ibid* p. 192). Thus, if a plant has a large lime-requirement, then the liberation of calcium-ions to the soil solution and its absorption by the plant roots must be rapid in order to meet the needs of that plant. The three main factors which, according to Truog, determine the lime-requirement of a plant are: (a) its normal lime content, (b) its rate of growth, (c) its feeding power, as determined by the character and extent of its root system. The first two factors operate in one direction, whilst the third operates in the other direction, the actual lime-requirement therefore being the resultant of all the three.

2. THE CORRELATION BETWEEN THE REACTION OF PLANT SAP AND THAT OF THE SOIL SOLUTION.

Truog (*ibid*) has presented much experimental evidence to show that there exists a close correspondence between the lime-requirements of numerous species of plants and their response to the liming of acid soils that support them, or reciprocally, to their ability to withstand acid soil conditions.

As a corollary to these conclusions, Truog and Meacham [76] have estimated the degree of acidity of the expressed sap of several species of plants grown on acid soils, and state that 'unquestionably soil acidity in many cases affects the acidity of the juice or protoplasm of these plants by limiting the supply of available lime' (*ibid*, p 473). This is presumably because the by-products of plant metabolism are in the main acidic in nature.

The whole question, however, needs to be placed on a sound physiological basis, for there are certain objections to the statements made and to the experimental methods employed by the above-named investigators. Thus the acidity of the plant saps was estimated on the saps that were obtained merely by the application of pressure, and this would not be expected to yield liquids that are identical in composition or concentration with the contents of the cell vacuoles.† That the intensity of acidity of the cell sap of plants is an important factor in the regulation of the activities of the enzymes present in it has been shown by physiological research.* Each species of plant contains cell sap whose hydrogen-ion concentration appears to be specifically adapted to the physiological processes of that plant, and is maintained at a constant value mainly by the buffering effect of certain solutes in the sap.

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† See 'Some recent researches in Plant Physiology,' W. R. G. Atkins, London, 1916 ; Macmillan.

* For references see Clark's 'Determination of Hydrogen-ions' [11] p. 230, and Clevenger,[13] pp. 217-18.

The question of the acidity of plant saps in relation to various environmental factors governing plant growth has also been investigated by Clevenger [13] and by Haas [29]. The former found a definite correlation between the intensity of acidity in the sap of roots of certain plants, and that of the soil solution of the acid soils in which they were growing. No simple correlation was found for the sap of stem and leaves. In some cases the addition of lime to the soils, by providing a stimulant to the growth processes of plants, appears to cause a rise in the rate of production of acid substances within the plant tissues in stem and leaf, and hence to produce a higher intensity of acidity in the sap of these tissues. The reaction of the root sap under this treatment may remain unaltered.

Although the relationships between soil conditions and the anabolic and katabolic transformations that occur in plants cannot yet be said to be clearly established, there is here an interesting field of research which promises results of far-reaching importance

That the total calcium content of a soil is one of the major factors influencing plant growth is no longer doubted, but only the most careful and thorough investigation can be hoped to establish the cause of the unproductivity of any particular example of a sour soil as being definitely due to deficiency of calcium, The work of Shedd [70] on the lime-deficient soils of Kentucky, for example, led him to conclude, from the fact that the more fertile of these soils contained the higher proportions of cf calcium, that the cause of infertility here was lack of calcium No detailed analysis of other factors that might have been responsible for low productivity, such as the presence of excess of hydrogen-ion or of toxic metallic-ion, was attempted, so that Shedd's conclusion as published, would seem to need qualification. It would appear to be especially difficult to establish the unproductivity of any particular sour soil as being due to a deficiency of calcium compounds rather than to the inhibiting effect to plant growth of the several other factors presented by sour soils, and correlated with such calcium deficiency.

IV. THE TOXICITY OF ALUMINIUM, IRON, AND MANGANESE AS A FACTOR IN SOIL SOURNESS.

1. THE TOXIC EFFECT OF ALUMINIUM, IRON, AND MANGANESE ON PLANT GROWTH.

Many of the earlier workers on soil acidity problems observed that, when certain soils were extracted with solutions of neutral salts, the extracts were acid in character, and furthermore, that they contained a notably high concentration of aluminium, iron, and occasionally manganese.

Veitch in 1904 connected the two results, and attributed the presence of acid in the extracts to the hydrolysis of aluminium and iron salts brought into solution by basic exchange between certain soil minerals and the neutral salts added. (See p. 47).

Abbott, Conner and Smalley [1], during their examination of certain Indiana sour soils in 1913, concluded that the infertility of

these soils was largely due to the toxic effect of aluminium in the soil solution. They obtained water extracts of the soils, and showed that the reaction and toxicity of these extracts could be exactly matched in nutrient solutions which included aluminium nitrate and nitric acid in their make up.

Hartwell and Pember [32] in 1918 demonstrated that the extracts of certain sour soils which had been receiving continuous dressings of ammonium sulphate, and which could support only very inferior crops of barley, could be imitated by nutrient solutions containing aluminium sulphate, but not by nutrient solutions to which sulphuric acid had been added. This result definitely established the unproductiveness of the barley soils as being due to an excessive concentration of aluminium-ion and not to hydrogen-ion.

Mirasol in 1920 [48] performed an interesting series of experiments in which he demonstrated, amongst other facts, that aluminium salts, in the absence of calcium compounds, are highly toxic to sweet clover grown in sand-cultures. The medium was watered with solutions of aluminium salts of such composition that they possessed a reaction equivalent to that of an average sour soil, such as those subsequently examined in the investigation. Insoluble aluminium hydroxide ($Al(OH)_3$) mixed with the sand was shown not to have any toxic effect towards the plants. Furthermore, Mirasol showed that certain sour soils that had previously been submitted to the leaching action of a neutral salt solution (potassium nitrate), so that a large amount of the more easily decomposed aluminium compounds in them had been removed, were better able to support the clover crop. Whilst iron and manganese are probably contributory factors in the infertility of certain sour soils, Mirasol considers that the preponderance of evidence points to aluminium as the determining factor, at least in the cases investigated by him.

Plant physiologists have demonstrated by numerous nutrient solution experiments that, whereas aluminium-ion in low concentration may have some stimulating effect on plant growth, it becomes markedly toxic when it exceeds the concentration of aluminium-ion occurring in a solution of aluminium sulphate containing 0·0342 grams of the compound per litre, viz. a solution of 0·0001 normality. (Mirasol, [48] p. 160.) The toxicity of iron and of manganese salts has also been demonstrated and standardized in a similar way. There would appear to be no doubt, therefore, that, in those sour soils that contain toxic amounts in the soil solution of aluminium-ion (or of iron or manganese-ion in toxic amount), infertility is in the main due to the presence of excess of these organic toxins, and not necessarily to the presence of excess of hydrogen-ion which, for reasons already explained, usually accompanies them.

In actual practice it is impossible to estimate the concentration of aluminium-ion (or of iron or manganese-ion) in a soil solution or extract with any degree of precision. As far as the writer is aware, no accurate method for the determination of the concentration of these metallic-ions in solutions, along the lines of the electrometric hydrogen electrode method for hydrogen-ion estimation, has yet been elaborated. The only

simple way in which toxicity due to aluminium-ion etc. in a soil solution can be demonstrated is first to determine the total quantity of the element in a certain volume of the solution, or in an equivalent volume of the soil-extract by conventional gravimetric or volumetric means, and then to compare the figure obtained in this quantitative estimation with the results of analyses of nutrient solutions containing varying amounts of the toxic elements, and possessing known degrees of toxicity towards plant growth. An alternative way is to use the water extract of the sour soil whose unproductivity is suspected to be due to the presence of inorganic toxins, as a nutrient medium in which to grow test plants, or to water sand cultures of the test plants.

2. THE ORIGIN OF SALTS OF ALUMINIUM, IRON, AND MANGANESE IN THE SOIL SOLUTION.

Aluminium occurs in the mineral portion of soils chiefly in certain complex silicates of which the felspars and certain of the ferro-magnesian minerals (e.g. mica, augite, hornblende, etc.) are the most abundant. It also occurs as phosphate and oxide, and possibly also as various hydroxides. Iron occurs chiefly in ferro-magnesian minerals (e.g. biotite, augite, hornblende, olivine), and as oxide (magnetite, etc.) and hydroxide (limonite). Manganese is of rare occurrence, and is occasionally found in ferro-magnesian minerals and less commonly as oxide.

Soil analyses have shown that the largest quantity of the three metals mentioned is present. in the finest particles of the soil. During the weathering of rocks rich in silicate minerals a residue containing a large proportion of kaolinite is left (see p. 47). Under certain conditions lateritization rather than kaolinization goes on, and the ultimate products of weathering them consist chiefly of aluminium hydroxides and iron hydroxide.

Of the three known aluminium hydroxides, gibbsite $Al_2O_3 3H_2O$) alone is soluble in dilute acids and alkalies. None of the hydroxides dissolve in water (Olsen, quoted by Mirasol,[48] p. 164). In sour soils, which contain in their soil solutions injurious amounts of aluminium-ions, gibbsite must therefore be the compound which chiefly gives rise to these ions, for all the other aluminium compounds enumerated above are either quite insoluble and stable, or are only very slightly decomposable under the conditions that occur in soils. There has been some doubt cast as to the actual occurrence of gibbsite and the other hydroxides of aluminium in soils, especially soils of northern latitudes. Cameron and Bell, for instance, state that neither gibbsite nor bauxite occur in the great majority of the United States soils [9]. Other investigators have brought forward evidence against this conclusion, and Mirasol ([48] p. 165), summing up the data, expresses the opinion that, at least in sour soils containing toxic amounts of aluminium, the compound furnishing the aluminium is undoubtedly gibbsite. In tropical countries, the presence in soils of aluminium hydroxides, including the easily decomposable gibbsite, is more than likely, since lateritization is the type of weathering that commonly goes on in those countries.

According to Hilgard *, in order to detect the presence of aluminium hydroxides in soils by chemical analysis, as contrasted with the actual identification of the minerals by mineralogical examination, the percentage amounts of aluminium oxide (alumina) and of silica, soluble in hydrochloric acid under the conditions observed in conventional soil analysis, should first be estimated. Now silica and alumina are combined in kaolinite which, apart from the hydroxides, is the chief form in which aluminium occurs in soils. In kaolinite, silica and aluminia are combined in the ratio of 46 : 40 per cent. The remaining 14 per cent. is water of hydration. If the analytical figures show an appreciable amount of acid-soluble aluminia over and above that required to combine with the acid-soluble silica to satisfy the quantitative ratio stated, the conclusion may safely be drawn that free aluminium hydroxide exists in the soil, and that this, because of its solubility in the acid, is probably gibbsite. In this way, then, one may gain information as to the cause of infertility in cases of sour soils that are deficient in easily soluble bases, for if the analytical figures obtained in the conventional chemical analyses of such soils exhibit the particular quantitative relationship between aluminia and silica stated above to be indicative of the existence in those soils of free aluminium hydroxide, it is more than likely that their soil solutions will contain aluminium in toxic amount.

Spurway [72] has carried the application of this principle to a further conclusion in his examination of certain glacial sour soils of Michigan. He found a definite correlation between the ratios of calcium oxide to iron and aluminium oxides soluble in dilute hydrochloric acid and the reaction of the soils. All the soils with acid reactions to litmus gave ratios $CaO : (Fe_2O_3 + Al_2O_3)$ above 1 : 1·3, and all soils with alkaline reactions gave ratios below this figure.

Howard [39], in a study of the variations in the intensity of soil acidity occasioned by the applications of dressings of sodium nitrate and ammonium sulphate to certain soils of the Rhode Island Experiment Station, came to the conclusion that in the acid unlimed soils, iron and aluminium oxides as bases, partly take the place of calcium and magnesium oxides in the limed soils. Furthermore, the concentration of hydrogen-ion in the soil solution of the unlimed soils receiving ammonium sulphate was found to be very similar to that produced by the addition of certain amounts of aluminium salts to neutral buffer solutions. Howard used Gillespie's colorimetric method for determining hydrogen-ion concentration. The conclusions appended to Howard's paper are worthy of quotation *in extenso*, not only because they explain the effect of continued treatments of soils deficient in easily-soluble bases with dressings of ammonium sulphate, but also because they sum up the reasons why certain sour soils possess an acid reaction, as well as a varying concentration of aluminium-ion and of iron-ion in the soil solution. Howard writes : 'The acidity in a soil caused by the long-continued use of ammonium sulphate is the result of a change in the ratio of acids to bases. The position normally occupied by

*Hilgard's 'Soils.' Macmillan. New York, 1918. p. 101.

the stronger bases such as calcium and magnesium, has been taken by the weaker bases such as iron and aluminium. The neutrality of the soil solution can no longer be maintained since salts of these weak bases dissociate.* Free acids resulting from this dissociation is accompanied by a definite concentration of hydrogen-ions' (*loc. cit.* p. 320).

Comber [1] has accepted in principle the above conception of the causal association of iron and aluminium-ions and hydrogen-ions in the soil solution of sour soils, and has directed attention to it in support of a quantitative test for sour soils which he has discovered. Comber applied an alcoholic solution of potassium thiocynate to samples of Yorkshire soils, and found that those soils which, in a previous examination had been found to be deficient in easily-soluble base by the Hutchinson-McLennan lime requirement method, imparted a blood-red colour to the reagent through the formation of ferric thiocyanate by the exchange of potassium-ion for ferric-ion in the soil solution.

Let us now consider how aluminium, iron, and manganese-bearing minerals in the soil may give rise to ions of these metals in the soil solution. Analyses of soil extracts have shown that the soluble chlorides, sulphates, and nitrates of the three metals may all be present in the soil solution. The amount of chloride and of sulphate will naturally be limited by the amount of chlorine and of sulphur in the soil. Under certain conditions, soils rich in sulphur may contain considerable quantities of aluminium and manganese sulphates, as was shown by Ames and Boltz [2].

Nitrification is a normal process in soils, and when most active, comparatively large quantities of nitrates of aluminium, iron, and manganese may be formed, provided that other more easily soluble bases, such as calcium and magnesium compounds are not present to excess. (Potassium and sodium compounds such as the carbonates liberated during rock weathering can never neutralize all the nitric acid formed during nitrification, since these compounds are extremely soluble, and are usually leached out of the soil, unless absorbed by plant roots, almost as fast as they are formed.)

The conclusion reached by a consideration of these facts is that many sour soils that is soils deficient in easily soluble bases (calcium and magnesium compounds), may be expected to contain in their soil solutions an appreciable concentration of ions of aluminium, iron, and manganese, either together or severally. When this concentration of ions rises above a certain figure, the soils will be more or less infertile to most agricultural plants because of the toxicity of these ions in the soil solution. Accompanying the ions of aluminium, iron, and manganese, there will always be a corresponding concentration of hydrogen ion in excess of that normally present in pure water. The sour soils will thus show an acid reaction towards indicators.

It does not necessarily follow, however, that the *total* hydrogen-ion concentration in the soil solution of all sour soils

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* i. e. hydrolytic dissociation, e. g. $Al_2(SO_4)_3 + 6\ H_2O \rightleftarrows 2Al(OH)_3 + 3H_2SO_4$

is due entirely to the hydrolysis of salts of aluminium, iron, and manganese. Certain peat soils, for example, may possess acidic soil solutions because of the ionization of organic acids present in them. Badly drained soils rich in humus may show this characteristic through lack of sufficient aeration whereby the organic acids are prevented from becoming oxidized (p. 75). Mineral soils also may show an acid reaction towards indicators, owing to the presence of definite mineral acids in them (p. 47). Knight [42], for example, has demonstrated the possibility of certain acid mineral soils containing in the soil solution hydrogen-ions due to the ionization of inorganic mineral acids, in addition to those due to hydrolysis of aluminium, iron, or manganese salts.

3. THE SPECIAL CASE OF MANGANESE IN THE SOILS.

The peculiar relationship of manganese to plant growth is worthy of separate mention, since recently much stress has been laid on the rôle which manganese compounds play in the plant and in the soil.

It has long been known that manganese occurs in a great many plants LeClerc in 1872 found the element in most of the soils and plants examined by him. In 1896, Bertrand showed that manganese plays an important part in the process of oxidation in plant metabolism. This aspect of the subject will be more fully considered in the next section.

Although numerous field trials have demonstrated the undoubted manurial value of manganese salts applied to certain kinds of soil, it has been found that dressings of over 40 lb. of manganese per acre are usually detrimental rather than beneficial.

Cases of sour soils which owe their unproductivity to the presence of excessive amounts of manganese in the soil solution have been recorded. Funchess [21] was given reason to suspect that certain soils of the Alabama Experiment Station were infertile from this cause, although later [22] he somewhat modified his opinion, and laid more stress on the inhibitory effect of an excessive concentration of hydrogen-ion in the soil solution presumably brought about by the hydrolysis of manganese salts chiefly. Robinson, Gardiner, and Holmes [62] summarized the results of experiments on certain sour soils in which they found a maximum amount of water-soluble manganese equivalent to 24 parts of MnO per million of soil extract. This concentration of manganese they considered to be large enough to exercise a toxic effect on the bacterial flora of the soil, and also to have a direct harmful effect on plant growth.

Mirasol's experiments [48] also indicated the importance of manganese as a toxic soil constituent. It would appear that infertility due to the presence of an excessive concentration of manganese-ion in the soil solution is of rare occurrence however, and that the element most frequently found to be toxic in soils is aluminium and not manganese.

V. THE ABSENCE OF ADEQUATE AERATION AS A FACTOR IN SOIL SOURNESS.

OXIDATION PROCESSES IN SOILS AND THE FACTORS CONTROLLING THEM.

Soils whose sourness can definitely be traced to poor aeration as the major factor responsible for their infertility, constitute an important class the study of which is of particular interest in humid tropical countries. Poor aeration is primarily caused by imperfect drainage, and this in turn is the result of many factors, of which the nature of the substrata underlying a soil, the topographical position of the area containing it, and tilth are the chief.

The tilth of a soil may be defined as that state of a soil which is decided by the relative sizes of the constituent particles, and the way in which these particles are arranged. Sandy soils in most cases possess a good tilth ; clay soils in general are wet and sticky. But certain clay soils frequently exhibit a good tilth because of the aggregation of their ultimate particles into floccules, and of these floccules into crumb. It is the chief aim of the clay land farmer to build up in his soil compound particles by cultivation. This involves careful tillage, manuring with dung and green dressings, and liming. The addition of various artificial fertilizers to soils has frequently been found to result in great alterations in soil tilth. Nitrate of soda and sulphate of potash are said to destroy tilth, whereas lime frequently brings about great improvement because of the marked flocculation which it induces.

Thus the presence of lime in a soil is one of the main factors which are responsible for good tilth. Not all soils rich in lime possess a good tilth for that reason alone however, but in general, water-logged soils containing lime can be more readily brought into a satisfactory state as regards tilth by artificial drainage and tillage than can similar soils deficient in lime. In this connexion, therefore, tilth is a factor often positively correlated with the amount of lime in a soil, and consequently so also is aeration in so far as this condition is decided by tilth.

It is unnecessary to discuss the exact meaning of tilth, or to go into the physico-chemical theories that have been brought forward to explain it, since we are only concerned here with the effect which poor aeration produces on the chemical changes in soils resulting usually in the formation of substances of acidic reaction.

The lack of ventilation in water-logged or compacted soils greatly minimises the amount of free oxygen that can come into contact with the soil constituents, so that in such soils oxidation is either altogether absent, or proceeds but slowly. The importance of oxidation in soils has been insisted upon by many investigators, notably by Schreiner and his collaborators at the United States Bureau of Plant Industry, who have shown that certain toxic organic substances tend to accumulate in soils of low oxidizing power (see 77). The very extensive research undertaken by these men is based

on the work of Whitney, who was the first to point out the important relationships that exist between fertility and the composition of the soil solution. Whitney claimed that the soil solution of almost all soils is of approximately the same composition and concentration. Hence infertility cannot be due to a lack of plant nutrients in unproductive soils ; it must therefore be due to the presence of some soluble toxin. Fertilizers were supposed by Whitney to precipitate toxins from the soil solution, and to owe their beneficial effects to this and to other indirect actions in the soil.

Pickering's investigations at the Woburn Fruit Farm [56] have clearly shown that the roots of many plants give rise to soluble toxins which adversely affect the growth of other plants in the immediate vicinity. These toxins are apparently readily decomposed in the soil, for laboratory tests failed to reveal their presence in the soil extract. The toxic effect of one plant on another was shown to be most marked in badly aerated soils. These results are in full agreement with Whitney's views.

Schreiner and his collaborators* commenced in 1907 to make a careful search in the soil for such organic compounds as could be identified. They concurrently studied the effect these and of similar compounds on plant growth in a series of nutrient culture solution experiments. Certain compounds such as dihydroxystearic acid, guanidine, vanillin salicylic aldehyde, and picolinecarboxylic acid were in this way found to be toxic to plants, and it was demonstrated that certain of these substances are almost invariably present to excess in badly drained, badly aerated, compacted, and lime-deficient soils, such as would be classified as typical sour soils. The majority of these compounds are evidently decomposition products of plant residues, or are actual plant excretions, and, being in some cases acidic in nature, are doubtless responsible, in part at least, for the excessive concentration of hydrogen-ion in the soil solution of soils of low oxidizing power

Rigg [60] prepared solutions from the decay products of the rhizomes of *Nymphaea*, and found that these had a markedly toxic effect on plant growth. The solutions showed measurable acidity, but after the neutralization of the acids present, they were found to have lost their toxicity.

Dachnowski [17] has attributed the toxic effect of bog water to the presence of acidic products of the decay of plant residues in the absence of adequate aeration.

Soil oxidation has been studied in detail by Schreiner and Sullivan [68]. These investigators distinguish between the extracellular oxidation which living plant roots are apparently able to bring about at their surfaces on certain substances in the soil, and oxidation that proceeds in the soil itself. The mechanism of these oxidation processes is fully discussed, and a review of the extensive literature on the subject is given in the bulletin cited. Oxidation at the root surface and oxidation in the soil itself are probably of the same type. It is not yet definitely settled whether or no the process is controlled by enzyme activity. although the usually accepted idea up to the present time has been that oxidation by the plant and by plant extracts is due to

*See the various bulletins of the United States Department of Agriculture Bureau of Soils, especially Nos. 47 (1907), 56 (1909), 73, 74 (1910), and 87 (1912.)

oxidizing enzymes. It has been shown, however, that many, if not all, of the oxidations produced by the so-called enzymes can be brought about by non-enzymotic substances both organic (such as benzaldehyde, pyrogallic acid, quinone and certain organic peroxides), and inorganic (such as peroxides and salts of manganese, iron lead, etc.). Essentially oxidations in the soil consist firstly of the fixation of atmospheric oxygen in an active form by its entering into combination with certain organic substances with which it forms peroxides ; and secondly, the oxidation of easily oxidizable organic matter that has previously been produced by the action of micro-organisms on plant residues, by the transference to them from these peroxides of oxygen in an active or nascent state.

In the absence of oxygen, organic substances accumlate in the soil, and many of these, being of a toxic nature, inhibit plant growth and render the soil infertile.

It has been found that oxidation in the soil is increased by the addition of salts of manganese, iron, aluminium, calcium, and magnesium, especially in the presence of simple hydroxyacids, such as citric tartaric, malic, glycollic acids and their salts. The best oxidation is obtained by the addition of manganese salts to soils. It has long been known that manganese stimulates plant growth when introduced in not too great amount into the media in which plants are rooted. It appears that certain compounds of this metal have the power of bringing about rapid oxidation, especially when combined in some way or acting in conjunction with certain organic substances, such as the hydroxyacids and their salts, already mentioned. The part played by manganese in the internal oxidation processes that go on in living plants may perhaps be accounted for in this way. Indeed, Bertrand held that many of the so-called plant oxidases, actually consist of some active complement, usually a manganese salt, combined with an activating complement which may be protein in nature.

Possibly the increased oxidative activity which proceeds in soils when manganese salts are applied to them as manurial dressings, may thus be due to the formation of oxidase-like catalists in the soil, or to the augmentation of the supply of similar catalists already present therein.

Skinner and Sullivan [71], and later Brown and Menges [7], showed that manganese, in addition to influencing oxidation, stimulates the activity of micro-organisms in the soil, especially of the bacteria of ammonification and of nitrification.

It has frequently been demonstrated, on the other hand, that excess of manganese in the soil may prove highly injurious, as has already been mentioned in the last section.

Soils whose infertility is due to the presence of toxic organic compounds formed under conditions of poor aeration may generally be made productive by proper draining, followed by the application of lime and other soil amendments, possibly including manganese compounds. The change in conditions brought about by these operations allows the oxidizing agents present in the soil to exercise their full effect, and thus to cause the destruction of the toxic substances by breaking them down into simpler and inocuous oxidation products.

It has been suggested above that this process of oxidation is controlled in every case by certain compounds present in the soil itself, but it appears from the recent work of Robbin and his collaborators [61] that, in certain cases at least, bacterial activity is the agent directly responsible for the decomposition of the toxic organic substances. Robbins has shown that there exists in soils a limited number of species of bacteria which are able to destroy vanillin. This substance is one of the toxins that has been isolated from certain soils. Those conditions which favour rapid oxidation also encourage the maxium activity of the vanillin bacteria, for good aeration and an alkaline reaction in the soil have been shown to furnish the optimum conditions for their development.

2. THE PRESENCE OF PROTOZOA IN SOILS.

No account of soil sourness would be complete without some reference to the protozoan fauna of the soil. Russell and his collaborators* have demonstrated at Rothamsted that in many soils two groups of organisms normally occur; one set includes the beneficial bacteria which play an active part in such important processes as humus formation, nitrification and nitrogen fixation, and the other set includes certain protozoa that apparently are able to destroy organisms of the first class, and may thus be detrimental in their effect on fertility in certain cases.

In well aerated, highly productive soils, protozoa are probably present in negligible quantities, but in soils that are poorly aerated and exhausted by repeated cropping, the protozoan fauna may be very prolific, and may become one of the factors responsible for the unproductiveness of those soils. Greenhouse soils are said to be especially prone to such degeneration. Infertile soils of this type have been termed 'sick' soils.

It has long been known that many soils are altered by antiseptics, such as carbon bisulphide, which were first applied to soils in order to kill insect pests. It was shown in 1893 that the bacterial flora undergoes a marked change when the soil is treated with carbon bisulphide. First a great decrease in the number of organisms capable of developing on gelatin plates is noted. This is followed by a striking increase in bacteria, the number rising far higher than it was before, and the new flora having a somewhat different composition from the old. The result is found to be similar when antiseptics other than carbon bisulphide are employed. Certain sewage investigators also noticed an increase in bacterial numbers in sand filters after disinfection.

That heating soils increases their productivity has also long been known. Although the effect of heat may partly be accounted for on the assumption that heating alters the physico-chemical properties of soils, in such a way that the production of plant

* A full account of the Rothamsted work is given by Russell in his book 'Soil conditions and plant growth'. (64.) The whole subject of soil protozoa investigations is reviewed in a lengthy article in *Soil Science*, 171, 1911, pp. 197-269, by Kopeloff and Coleman

nutrients is accelerated, it undoubtedly also exercises some effect on the micro-organic flora and fauna. Russell and his collaborators have investigated the problem, and have shown that partial sterilization of certain soils by heat or by antiseptics causes a fall and then a rise in bacterial numbers, the latter change being accompanied by an increase in ammonification.

The evidence accumulated was interpreted as furnishing proof that these and other results are due to the existence in certain soils of some limiting factor, which is of the nature of living organisms, and which is probably protozoan. At first no direct evidence of the actual occurrence of protozoa in soils was forthcoming, but recently several investigators have identified definite species of protozoa in certain soils in many parts of the world.

Soil protozoa apparently possess the power of ingesting certain bacteria, including the beneficial bacteria present in soils, and in this way their occurrence to excess in certain soils may be highly detrimental.

Soil protozoa can easily be destroyed by partial sterilization by the use of anticeptics, or by heating. Thus sick greenhouse soils have been improved by heating the soils by means of steam pipes. Certain soils are apparently improved by partial sterilization brought about by the application of quicklime [40]. Loew has described the sick soils of Porto Rico [44], and, as the result of numerous experiments, has come to the conclusion that the infertility of these soils is largely due to the presence in them of an undesirable micro-organic population. He recommended the use of carbon bisulphide as an ameliorator, but pointed out that if the soils be properly aerated and exposed to the germicidal effect of the sun's rays by deep ploughing, the same result would probably follow. It is worthy of note that the sick soils referred to by Loew are red clay soils possessing a marked acid reaction. On the whole, there appears to be no very direct evidence that soil protozoa play an important rôle as a factor limiting plant growth in normal well aerated soils. Possibly, in certain badly ventilated sour soils, such as the so-called sick soils of greenhouses, the presence of protozoa may be in part responsible for lack of fertility. Proper aeration, accompanied when needed by liming, will in most cases probably bring about a suppression of the undesirable micro-organic life concurrently with the destruction of harmful organic toxic substances, and a general improvement in the physico-chemical soil conditions.

Bad aeration may inhibit the activities of beneficial micro-organisms in the soil, apart from the encouragement it gives to the development of their protozoan enemies. Since nitrification is the result of an oxidation reaction, it is undoubtedly affected by aeration as well as by acidity Thus Schlösing [18] in 1868 noted that there was a rapid loss of nitrates when a moist humic soil was kept in an atmosphere of nitrogen Warington in 1880 found that saturating a normal soil with water caused it rapidly to lose the nitrates it contained. Kelley [41] showed also that flooded rice fields contain little or no nitrates. Possibly these results may in part have been accounted for by the activities of bacteria of denitrification. These live under anaerobic conditions,

and have been shown to reduce nitrates in water-logged soils to nitrites and gaseous nitrogen (see Russell, 61, p 131).

3. METHODS OF DETECTING AND OF ESTIMATING OXIDATIVE ACTIVITY IN SOILS.

It has long been known that during the oxidation of organic substances in soils, oxygen is absorbed and carbon dioxide is evolved. The earlier workers believed that oxidation in soils was entirely controlled by micro-organisms. Several points of similarity were noted between soil oxidation and bacterial activity, such as, for instance, the effect of heat on the two processes.

(a) Russell [63] in 1905 studied oxidation by estimating the oxygen absorbed by soils. He found that the same factors which influence fertility also influence the rate of oxidation, and apparently to the same extent. The relative fertility of different arable soils of the same type may be approximately estimated by comparing their rates of oxidation. Russell concluded that the amount of oxygen absorbed by soils measures the total micro-organic action, which, by producing enzymes, hastens decomposition. He proved that the quantity of carbon dioxide evolved is not necessarily proportional to the quantity of oxygen absorbed during oxidation in soils, for many soils have a great power of absorbing carbon dioxide.

Russell's method of estimating oxidative activity in soils by measuring the amount of oxygen absorbed, is difficult and tedious to carry out, and is open to the objection that it takes no account of the respiratory needs of the micro-organic flora and fauna of the soil.

(b) A better method, which to the knowledge of the writer has never yet been employed in soil studies, would appear to be some modification of Bunzel's method.* This method is largely used by plant physiologists for measuring oxidase activity in plant saps. It depends on the fact that the rate of oxidation of pyrogallol by the oxygen of the atmosphere is accelerated by the presence of an oxidase in it. A special form of reaction flask is used. This is fitted with a manometer by means of which the decrease in pressure of its gaseous contents caused by the absorption of oxygen during the reaction can accurately be measured. For soil work, some modification in the design of the reaction flask would have to be made, but even then the method would be open to the opjection raised in connection with Russell's method, namely that it takes no account o the respiration of the micro-organisms in the soil.

Schreiner and Sullivan [68] recommended the use of certain easily oxidized organic compounds which yield highly coloured products when brought into contact with oxidizing agents. They found an aqueous solution of aloin of 0 125 per cent. strength to give the best results. Twenty grams of soil are

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* See Atkin's 'Some recent researches in Plant Physiology,' p. 241—8 London, Macmillan, 1916.

shaken four or five times with 50 c. c. of the solution during the course of an hour, and then allowed to settle. If the solution is turbid, 50 c. c. of 95 per cent. alcohol are added to flocculate the soil and to extract the reagent. The mixture is then centrifuged, the supernatant liquid poured off, and the depth of colour in the solution compared with some standard in a colorimeter.

Besides aloin, gum guiacum, pyrogallol, hydroquinone, Alpha napthylamine and benzidine may be used to indicate or to estimate the oxidizing power of a soil.

(d) One of the most general and delicate reagents for recognizing the oxidizing property is hydriodic acid. This reagent has long been used in chemistry. Gerretsen [49] has used it with success in an examination of the sugar-cane soils of Java. An acidified 1 per cent. solution of potassium iodide is left for five minutes in contact with 2 grams of soil which is then quickly separated by centrifugation. The amount of iodine set free is estimated by a centinormal solution of sodium hyposulphite. The oxidizing power of the soil is expressed in miligrams of iodine per 100 grams of soil.

Gillespie [27] has recently drawn attention to the fact that oxidation in soils is the converse of reduction, and that a sharp line can be drawn theoretically between the two processes, taking as standard, the properties of pure water. This conception is an exact parellelism with the idea of acidity and alkalinity ; and just as in the latter case acidity is purely a relative term, so also is oxidation. Further, it has been shown that a neutral reaction is not necessarily the optimum condition for soils, but that a slightly acid reaction is more desirable. It is similarly true that the theoretical point between oxidation and reduction is probably not the best condition for soils. Differences in acid intensity have been studied in soils by electrometric potentiometer methods, and Gillespie proposes a similar method for estimating the reduction potential of bacterial cultures and soils. In this way he has furnished the soil chemist with a method of measuring the intensity of oxidation in a soil as contrasted with the total quantity of oxidation as estimated by former methods such as those already described.

Gillespie, in discussing the question of acidity in soils, expresses doubt as to whether the injurious effects of poor drainage on vegetation are due entirely to the high degree of acidity usually exhibited by badly drained soils. It would appear more likely that they are due to their high reducing power, which means the absence of adequate oxidation, and the consequent accumulation of organic toxins, or of ferrous compounds in such soils. Gillespie's investigations have shown that bacterial cultures are normally reducing, and it would appear to follow that the reducing power of water-logged soils may be due to the effect of bacterial activity, irrespective and independent of the chemical reactions involved in producing the reduction potential.

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STUDIES IN WEST INDIAN SOILS.

I. THE SOILS OF DOMINICA, THEIR GENESIS AND FERTILITY CONSIDERED IN RELATION TO REACTION.*

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INTRODUCTORY.

PART I. THE GENESIS OF THE SOILS OF DOMINICA.

(A) The Main Geological features of Dominica.
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SUMMARY.

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INTRODUCTORY.

During a visit to Dominica extending from October 29 to December 6, 1920, the writer made a preliminary investigation into certain problems connected with the soils of that island, the results of which are set out in the following pages.

Recently the particular question of soil acidity has received some attention from various workers in the West Indies, notably in Antigua, St. Kitts and Dominica, and the data obtained in these investigations have been brought together in a paper by Sir Francis Watts, published in 1917 in the *West Indian Bulletin*[24].* The writer of that paper comments on the fact that, whereas certain West Indian soils growing such crops as sugar-cane, cacao and limes, regularly give satisfactory yields, and appear to be quite capable of supporting healthy and vigorous plants, yet many of them exhibit large lime requirements, and, according to the usual interpretation of this property, are to be classed as acid soils.

The term *acidity*, as used in its application to soils, possesses a meaning which has rarely been clearly defined in the past by agronomists. In order to obtain a clear understanding as to the meaning of soil acidity, the writer has attempted in another paper to summarize the results of recent investigations in this field of soil science, and to discuss the various factors which are responsible for the well-known characteristics of so-called acid soils. It is stated in that article that soil acidity, by its chemical definition as that condition of a soil which is due to the presence of excess of hydrogen-ions in the soil solution, is actually only one part of a broader conception to which the term *soil sourness* may be applied.

Sour soils present to plants many features not possessed by normal soils. These features, and the factors responsible for them, have been described in some detail in the article mentioned, and need only be summarily reconsidered here. Soils whose soil solutions contain an excess of hydrogen-ions, usually show, in addition, a deficiency in calcium. In many cases also, they contain excessive amounts of soluble toxic organic and inorganic compounds, such as salts of aluminium, iron and manganese. Finally, certain sour soils may contain an undesirable type of micro-organic fauna and flora.

The lime requirement of a soil which has often been proposed as a means of measuring soil acidity, does not give a true estimate of the *degree* of acidity. It may give some indication of the *quantity* of acid which may become reactive under certain conditions, and in a certain length of time, but it may also coincidently take some account of certain of the other factors above-mentioned. Part of the lime, for instance, may be removed in combining with toxic inorganic substances, or may be in part absorbed in producing those physical effects which are so frequently consequent on the liming of soils of poor tilth.

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* Reference is made by number to the bibliography tabulated in the appendix.

The occurrence of a considerable concentration of hydrogen-ion in a soil solution, unless present in high degree, is not in itself considered necessarily detrimental to plant growth. Indeed, many soil processes correlated with satisfactory plant growth, may best proceed in a medium of slightly acid reaction. It is only when the reaction of the soil solution is more acid than a reaction expressed by the pH value 5 *, that plant growth, at least for the majority of cultivated plants, may definitely be expected to suffer. In most sour soils it is the factors other than the presence of free acid that are probably responsible for infertiliyt. Frequently the lack of calcium compounds is the limiting factor for plant growth. In certain cases it is the presence of toxic amounts of aluminium, etc. In badly drained soils it is usually the lack of proper aeration which makes possible the accumulation of organic toxins, and the development of an undesirable micro-organic flora and fauna. Hence in examining the cause of infertility of sour soils which possess a markedly acid reaction, not only the hydrogen-ion concentration must be determined, but also the degree to which these other inhibitors of plant growth exercise their effect should be estimated.

It was with the primary object of finding how far the acidity of certain soils growing cacao and limes in Dominica could be correlated with their productivity, that the present investigation was undertaken. The recent elaboration by certain American scientists of quick methods for determining the hydrogen-ion concentration of soils, has made it possible to study the acidity factor more or less independently of the other factors. This has been attempted by the writer for a limited number of examples of the soil types occurring in Dominica.

The calcium carbonate content of soils is intimately bound up with the intensity of acidity of the soil solution, since calcium carbonate functions as a base when in contact with water. It also plays an important part in supplying plants with the necessary amount of calcium for the requirements of their metabolism and further, its presence in the soil solution appears to be essential to the maintenence of a proper balance of nutrients. Hence any soil investigation connected with questions of fertility should include determinations of the total amount of calcium, and of calcium carbonate in the soils examined. The writer has estimated the calcium carbonate content of several of the soils in Dominica, and has used the results, together with those obtained by other investigators, in an attempt to explain certain problems connected with Dominican soils. He wishes to acknowledge the great assistance afforded him by the published records of work already performed in Dominica, and especially the report on the soils of that island drawn up in 1902 by the Hon. (now Sir) Francis Watts. [22]

The plan of the following presentation is first to deal with the genesis of the soils of Dominica. This involves summary

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* Gillespie and Hurst. *Soil Science*, VI, 1918, p. 235.

consideration of the main geological features of the island, especially as regards the mineralogy and chemical composition of its rocks, together with a brief discussion of the main factors that have produced from these rocks the various types of soil at present existing in Dominica.

The second part of the paper is concerned with the reaction of the different soil types. In it are stated the collected experimental data which may be taken to indicate the condition of the soils as regards sourness or otherwise. These data are discussed in an attempt to decide which of the main factors most generally responsible for acidity in soils have been influential in impressing an acid reaction on those soils of Dominica that have been found to be sour.

The third part deals with certain definite areas where cacao and lime trees are growing, and where the effect of various growth factors on the cacao and lime plants can be most satisfactorily studied. Especial attention is given therein to the experimental plots at the Roseau Botanic Station.

Finally, the interesting case of the upland soils of Dominica that support a luxuriant forest flora receives special consideration in respect of the fertility of those soils, and the question of their value in the event of possible extensive development.

The writer desires to make it clear that this paper is chiefly intended to form the basis of future detailed work, the necessity for which will become evident when its scope has been examined. Numerous problems connected with the fertility of the soils of Dominica suggest themselves, and, since many of these problems are presented also by the soils of certain others of the West Indian islands, it was thought advisable to discuss the subject of soil genesis of a typical area of high rainfall in its broadest aspect, as a preliminary to more detailed research.

It is a privilege to be able to acknowledge the great assistance afforded the writer by the Curator of the Botanic Station (Mr. Joseph Jones), and by the Assistant Curator (Mr. Alfred Keys), whose aid in secu ing the soil samples was invaluable.

PART I. THE GENESIS OF THE SOILS OF DOMINICA.

(A) The Main Geological Features of Dominica.

Very little is known of the detailed geology of Dominica. Apparently only two original papers having direct bearing on the subject have so far been published [14,16].

Dominica is the most mountainous of the Antillean islands, both as regards the actual elevation of its highest parts, which reach a height of about 5,000 feet at Morne Diablotin, and the ruggedness and inaccessibility of its uplands. The central part of the island consists of a more or less continuous range of mountains, which runs north and south and gives off spurs to the sea. The valleys are numerous, and usually very deep and narrow. Cultivation is practically confined to the lower grounds near the sea, and to the valley bottoms and the basal parts of the steep slopes that border them. The interior is for the

most part covered with dense tropical forest, excepting in one or two districts, as for instance, the area of Crown Land opened up by the Imperial Road in the centre of the island. In these districts deforestation has been practised with a view to reclaiming the land for arboriculture.

The geological structure of Dominica is mainly volcanic. Exposures of rock in sea-cliff or river sections and in occasional excavations in the interior, indicate that fragmental ejecta, such as volcanic dust, ash and stones, together with a smaller proportion of lava, make up the bulk of the island. Extensive erosion caused by intense weathering and rapid transportation by running water has greatly obliterated the original forms of the once active volcanoes. The age of the oldest volcanic rocks is, geologically speaking, recent. They were possibly extruded in the Pleistocene era, since which period vulcanicity has frequently recurred in Dominica. The latest eruption took place in 1880 at the Grande Soufrière in the south-east of the island. The island still shows abundant solfataric action, and a boiling lake is one of its interesting features. These and other natural phenomena indicate the geological youth of Dominica.

Spencer[16] divides the rocks of Dominica into the following systems. :—

1. Basement of older volcanic rocks.

   These consist of lava flows (formed almost entirely of andesite, with possibly a few minor flows of more basic rocks) with massive compacted tuffs (ash beds) and breccias (beds of cemented angular rock fragments) overlying them. The basement rocks are exposed in the interior, but most of the high ground above 1,500 feet consists of *newer* volcanic accumulations.

2. Roseau tuffs.

   Beds of fine-grained material with occasional gravelly layers fill an old valley which occupied the site of the present Roseau River.

3. Gravel formations.

   True water-worn gravels occur at the Grand Savanna and at Morne Daniel on the leeward coast. They were probably accumulated as an ancient sea beach.

4. Coral beds.

   These occur on the surface of the gravels at Morne Daniel near Canefield estate, at a height of some 50 feet above the present sea level, and also to a lesser extent near Roseau, as for instance at Morne Bruce, at about 150 feet above sea-level.

The presence of beach gravels and coral beds, as well as many of the surface features of Dominica furnishes evidence of recent uplift, which has been accompanied by increased river erosion.

(B) The Origin of the Soils of Dominica.

1. The Weathering of Rocks.

The basis of most soils consists of the mineral fragments derived from pre-existing rock masses by processes of disintegra-

tion and weathering. The type of soil which accumulates over any particular area depends on many factors, of which climate and the composition of the original rock which gave rise to the soil, are the chief.*

Climate largely determines the kind of weathering to which exposed rocks are subjected. In tropical countries weathering is mainly brought about by the agency of water, which acts both mechanically and chemically on rocks. Mechanically, it disintegrates rock masses by forcefully impinging upon them as rain. Chemically, it brings about their comminution by dissolving away material which cements the more resistant grains, or by reacting with certain easily decomposed minerals of which the rocks are constituted so as to give rise to soft, amorphous products. Thus the various forms of felspar which are present in high proportion in most igneous rocks are hydrolyzed by water to form kaolinite, a white, friable, clayey substance, and certain more or less soluble compounds, such as silica and compounds of the alkali metals. The chemical activity of water is greatly enhanced by the presence of dissolved oxygen and carbon dioxide in it. Such natural water is capable not only of causing the hydrolysis of certain minerals, but also of bringing about the oxidation of iron compounds frequently present in them, and of acting upon and dissolving various forms of calcium carbonate. In the tropics, these effects are greatly accelerated by the high temperature which prevails.

The products of weathering of rocks either remain *in situ*, and there give rise to soils, or are carried away by agents of transport, such as wind and running water, and deposited in some region more or less remote from the place where they were originally formed. Thus we have sedentary soils and transported soils. In the tropics, running water is in general the most important agent of transport. It rapidly removes weathered material from exposed rock surfaces, especially on steeply sloping ground. Frequently, however, the presence of a dense covering of vegetation on a weathered rock surface almost entirely prevents transport by running water, but it is evident that unusually heavy or long-continued rainfall must have an effect in removing the finely divided material in all regions, except perhaps, in perfectly flat districts. The sudden downpours known as cloud bursts, in which a great volume of rain is concentrated into a small area for a short space of time, sometimes produce disastrous results, removing all the loose soil and subsoil down to the solid rock below.

In Dominica the effects of weathering and of transportation are well defined. It is important that they should receive attention if one wishes to understand the origin and chemical nature of the various soil types that occur in the island. At the outset, the mineralogical composition of the underlying rocks should be noted.

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*For a full description of the processes whereby rocks give rise to soils, the reader is referred to Rastall's, 'Agricultural Geology' *Cambridge University Press*, 1916.

2. THE MINERALOGICAL COMPOSITION OF THE VOLCANIC ROCKS OF DOMINICA.

Geological exploration in Dominica, as far as the writer is aware, has failed to reveal the presence of igneous rocks other than those belonging to the intermediate class of volcanic (or extruded) rocks, which includes the andesites and their fragmental equivalents (tuffs and breccias) that are produced by the explosive disruption of molten andesite during volcanic activity.* Possibly some more basic rock also occurs in Dominica, but this is of small account, and may be ignored in the general problem. The same type of igneous rock occurs in certain other West Indian islands, and during the outbursts in Martinique and St. Vincent in 1902, the products erupted in each case were closely similar in composition. The chain of West Indian islands indeed appears to be a branch of the Andean system of volcanoes, which coincides with a series of great parallel earth folds extending from South America to Mexico [7]. It has been pointed out by Iddings [8] that the volcanic rocks from this belt contain a preponderance of andesites and closely related rock types.

Andesite is a blue-grey, compact, finely-crystalline rock consisting of a definite assemblage of minerals, of which white glassy plagioclase felspar, and some dark-coloured ferro-magnesian mineral or minerals are the chief. Along with these, certain accessory minerals such as magnetite, apatite, olivine, etc. usually occur in small amount. According to the nature of the ferro-magnesian constituent, andesites are subdivided into hornblende-andesite, biotite-andesite, augite-andesite, and hypersthene-andesite. The andesites of Dominica apparently belong to the last-named class.

An examination of the mineral fragments derived from the volcanic rocks of Dominica during the process of soil formation has been made by Watts, who identified the following minerals in them[22]: plagioclase felspars (labradorite and anorthite chiefly), hypersthene, augite, hornblende, magnetite, epidote, quartz, nepheline, and natrolite. Much non-crystalline glassy material is also present. Of these minerals, the felspars and the three ferro-magnesian minerals together with magnetite, and possibly also nepheline, were doubtless originally present in the volcanic rocks from which the soils were formed. There is no mention of the occurrence of apatite, the only phosphatic mineral present in igneous rocks. The Dominican soils, as indicated by their analyses, contain an appreciable amount of phosphate, so that the original rock must have contained a certain proportion of apatite. Possibly it was confused in part with nepheline in the microscopic examination, for the two are very similar in optical properties.

Furthermore, the analyses show that potash occurs in noteworthy amounts in the soils although potassium-bearing minerals are rare in rocks of the andesite class, and are conspicuously

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*For an account of the classification of igneous rocks, the reader is referred to Hatch's 'Textbook of Petrology' London. *Swan Sonnenschein & Co.* 1918; and to Harker's 'Petrology for Students' *Cambridge Univ. Press*, 1920.

absent from the list of minerals identified in the Dominican soils. We are bound to conclude that the potassium supply in the andesite is located in the glassy non-crystalline fragments, whose nature and composition can not usually be determined by a mineralogical examination. This conclusion is in full accord with the composition of the volcanic ash thrown out in the St. Vincent eruption of 1902,* for actually in this ash, most of the potash was found to occur in the glassy particles.

Epidote, quartz, and natrolite (a zeolitic mineral) probably represent decomposition products of certain of the original rock minerals, for they are amongst the common secondary products produced by weathering of felspars and ferro-magnesian minerals.

3. THE WEATHERING OF THE MORE IMPORTANT MINERALS PRESENT IN THE VOLCANIC ROCKS OF DOMINICA.

i. *Plagioclase felspars.* The minerals of this group are double silicates of sodium or calcium and aluminium. Albite (soda felspar) has the formula $Na_2O \cdot Al_2O_3 \cdot 6SiO_2$, and anorthite (lime felspar) $CaO \cdot Al_2O_3 \cdot 2SiO_2$. Labradorite (lime-soda felspar) and andesine (soda-lime felspar) are isomorphous mixtures of these two extreme types. During weathering, the felspars are hydrolysed and yield kaolinite plus silica, and either sodium or calcium hydroxide or both, depending on the nature of the original felspar. e.g. (a): $Na_2O \cdot Al_2O_3 \cdot 6SiO_2 + 3\ H_2O \rightleftharpoons Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O + 4\ SiO_2 + 2KOH$.

(b) $CaO \cdot Al_2O_3 \cdot 2\ SiO_2 + 3\ H_2O \rightleftharpoons Al_2O_3\ 2SiO_2 \cdot 2H_2O + Ca\ (OH)_2$.

Kaolinite is a white substance which, in its purest form, constitutes china clay. Silica, when it forms one of the products of hydrolysis, usually combines with the alkaline hydroxide also liberated to form a silicate, which, being soluble, is removed in solution. Or the hydroxide may react with carbon dioxide in natural water to form a soluble carbonate or bicarbonate. Thus the lime-bearing felspars yield calcium bicarbonate as a soluble product of weathering. The great importance of this result will be discussed later. Actually the weathering of the plagioclase felspars is not so simple as outlined above. Lime felspars, for instance, in the presence of ferro-magnesian minerals, often give chlorite or epidote as intermediate products. Both these minerals occur in the Dominican soils.

In tropical countries, under certain conditions not yet fully understood, felspars give rise, not to silicates as previously described, but to various hydroxides of aluminium, the most important of which are gibbsite ($Al_2O_3 \cdot 3H_2O$), bauxite ($Al_2O_3 \cdot 2H_2O$), and diaspore ($Al_2O_3 \cdot H_2O$). All the bases and the greater part of the silica originally present in the felspars have been leached out and removed in solution. Weathering of this type is known as *lateritization*, and there are evidences of its incidence in certain parts of Dominica, especially in the wet upland regions. Prof J. B. Harrison has described the lateritization of fel-

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* See *Agricultural News*, I, 1902, p. 89.

spar of certain basic and intermediate rocks in British Guiana[9]. It is possible that the process is very common in many of the wetter West Indian islands where igneous rocks occur. It is of economic interest, in that it gives rise to workable raw materials (bauxite and gibbsite), which are largely used in the electrolyte manufacture of metallic aluminium.

ii. *Ferro-magnesian minerals.* Hypersthene is a double silicate of iron and magnesium. Augite and hornblende are double silicates of calcium, iron, and magnesium chiefly. During weathering, these minerals are converted into various silicates, such as epidote, chlorite and serpentine, often with separation of iron in the form of oxides or hydroxides (magnetite, haematite, limonite), together with carbonates and other compounds of very uncertain character and composition. Under conditions favourable to lateritization, as described in the last section, the sole insoluble product may be a mixture of aluminium hydroxide and ferric hydroxide of a bright-red colour; the calcium and magnesium compounds and the silica having been more or less completely removed by leaching.

4. THE CHIEF SOIL TYPES OF DOMINICA AND THE FACTORS RESPONSIBLE FOR THEIR DIFFERENTIATION.

In order to obtain some idea of the differences that are likely to exist between the soils occurring in the various topographical regions of Dominica, a consideration of the main factors that are responsible for the differentiation of soil types of the same geological origin would appear to form a logical introduction to the discussion.

The topography of a country largely decides the climate of its various parts Mountainous districts usually have the highest rainfall In insular countries, the windward side is usually more rainy than the leeward, except in those islands where the surface of the land is lowlying or only slightly elevated. In Dominica the distribution of the rainfall, as indicated by meteorological observations recorded at several stations,* permits of the subdivision of the island into three main regions, which may be designated and described as follows :—

1. The *central uplands* of elevation 1,000 feet up to 5,000 feet, and of mean annual rainfall of about 180 inches (variation 150 to 300 inches).
2. The *windward coastal belt*, including the north and the south coasts, from near Blenheim to near point Mulâtre, of mean annual rainfall of about 135 inches (variation 100 to 150 inches).
3. The *leeward coastal belt*, including the extreme north and south coasts of the island, and of mean annual rainfall of about 86 inches (variation 60 to 100 inches).

There is a fairly distinct alternation of dry and wet seasons in all these three regions, the former period extending from

* Annual Reports of the Dominica Botanic Station, 1909-19.

January to May, and the latter from June to December. The change from the wet season to the dry is occasioned by the setting in of the north-east trade wind, which blows with great regularity during the earlier months of the year, and prevents in some measure the formation of rain clouds.

A study of the geographical distribution of soil types over large areas of approximately uniform geological strata, such as exist in Russia, Germany and America, has shown that the dominant controlling factor is climatic rather than geological. Further, it has been demonstrated that rainfall is the climatic condition that is most potent in this connexion, temperature appearing to be of secondary importance *. In areas of comparatively small size, the effect of rainfall in deciding the ultimate composition and properties of soils is also of some moment. Its influence on the soils of such an area as Great Britain, where the variation in rainfall is only small, has been clearly indicated by soil surveys. We are justified, therefore, in expecting that the soils of Dominica might show appreciable differences when representative samples from the three climatic regions of the island are compared in detail. A study of the results of the analyses of typical Dominican soils, as presented in the Report previously alluded to[22] and summarized in the following table, indicates that this conclusion is fully warranted. Such a study enables one to form a fairly accurate estimate of the processes which have given rise to the soils that now exist in the three main climatic regions of Dominica.

The soil samples examined by Watts were twenty-three in number. They were taken from twenty estates or districts, which are divided between the three climatic regions as follows (see appended map) : –

1. *Central Uplands.* Middleham, Sylvania, Corona, Riversdale, Bona Vista, and Amelia.
2. *Windward Coastal belt* (including also the north and the south coasts). Blenheim, Hampstead, Melleville Hall, Castle Bruce, and Rosalie.
3. *Leeward Coastal belt.* Point Mulâtre, (South Chiltern),† Geneva, Roseau Botanic Station, (St. Aroment),† (La Haut),† Clarke Hall, Hatton Hall (now known as Picard), and Moore Park.

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* Rastall : ' Agricultural Geology ', p. 162.

†The districts named in brackets are not typical of the last region, as they are situated on elevated land of higher rainfall than that which is representative of the region.

TABLE I.

Chemical Composition of 20 per cent. Hydrochloric acid extract of Soil, expressed as Percentage of Dry Soil.

	Six Central Upland Estates.		Five Windward Coast Estates.		Six Leeward Coast Estates		Typical laterite soil, Madras, India.
	Mean value.	Limits of variation.	Mean value.	Limits of variation.	Mean value.	Limits of variation.	
Insoluble residue ...	51·10	±9·35	59·90	±10·39	71·37	±8·56	76·86
Soluble silica ...	0·27	±0·22	0·38	± 0·19	0·11	±0·04	—
Alumina (Al_2O_3) ...	9·40	±4·17	11·11	± 3·75	6·18	±3·09	8 84
Ferric oxide (Fe_2O_3)	10·23	±5·06	10·68	± 2·84	8 83	±4 36	10·09
Manganese oxide (MnO)	0·59	±0·50	0·45	± 0·43	0·05	±0 04	—
Lime (CaO)... ...	0·37	±0·18	0·33	± 0·26	1·34	±0·61	trace
Magnesia (MgO) ...	0·09	±0·08	0·08	± 0·05	0·24	±0·19	0·77
Potash (K_2O) ...	0·10	±0·03	0·08	± 0·02	0·10	±0·04	0·00
Soda (Na_2O) ...	0·17	±0·15	0·26	± 0·19	0·42	±0·27	0 17
Chloride (Cl) ...	0·005	±0·004	0·01	± 0·006	0 01	±0·01	—
Sulphate (SO_4) ...	0·09	±0·09	0·05	± 0 06	0·07	±0·04	—
Phosphate (P_2O_5) ...	0·08	±0·06	0·09	± 0·05	0·10	±0·05	trace
Combined water ...	11·31	±5·23	7·88	± 2 14	5·16	±3·91	2·87
Humus	7·14	±5·77	2·25	± 0·79	2 36	±0·91	
Calcium carbonate	0·34	±0·18	0·15	± 0·14	0·28	±0·25	0·24

DISCUSSION OF THE TABULATED RESULTS (TABLE I).

(a) *Lateritization.*

The general chemical composition of the Dominican soils, considered as a whole, resembles markedly that of typical lateritic soils such as occur in India. In the table, an example* of a lateritic soil from Madras, India, is included for comparison. The high percentage of acid-soluble matter in the Dominican soils (which cannot be correlated with a high carbonate content since this is actually low in the soils), and the high percentage of combined water, especially in the upland soils, are typical of lateritic soils, in which free aluminium hydroxides and iron hydroxide are present in abnormal proportions. The low percentage of soluble silica and of easily soluble bases is also typical of soils that have been exposed to continuous and excessive leaching action by water (see p. 91). The analytical figures show that the mean percentage of total acid-soluble matter, which includes the hydroxides of aluminium and iron hydroxides may be definitely correlated with the intensity of the rainfall, for in the leeward coast samples there is much more insoluble matter and considerably less aluminium and iron hydroxides than in the upland samples. Lateritization has apparently not gone on so completely in the drier regions as in those of high rainfall.

(b) *Leaching.*

The figures for the bases lime, magnesia, potash and soda show striking differences between the soils of the three climatic regions. It is usually assumed that 20 per cent. hydrochloric acid as employed in a soil analaysis, abstracts from soils amounts of these bases approximately proportional to the total quantities present, and more especially, that it completely decomposes all compounds of the alkali metals except the more stable complex silicates. The differences mentioned may now be interpreted as follows.

Of the bases lime, magnesia, potash and soda, the first two are usually more readily leached out of soils than the last two. Thus in relation to leaching at Rothamsted, Russell writes :† 'As might be expected from the known absorbtive properties of clay and of humus, drainage water contains mere traces of NH_4 and PO_4, and only little K; it contains chiefly carbonic acid, SiO_3, Cl, SO_4, NO_3, Ca, with some Fe, Mg and Na.' The wastage in drainage water at the same station was found, on the average, to be, per acre per annum: lime, 98 to 226 lb.; magnesia, 5 to 20 lb. and potash, 3 to 12 lb.

An extensive series of experiments has been carried out at the Florida Agricultural Experiment Station (see *Bull* 132, Nov 1916) in order to test the loss of nutrient substances from soils by leaching. The results of five years' work indicate that, in so far as the conditions obtaining in Florida are concerned,

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*Quoted by Rastall 'Agricultural Geology', p. 161.

† Russell : 'Soil conditions and plant growth' London *Longman's Green*, 1917, p. 69.

newly cleared land, when exposed to heavy rainfall soon loses much of its fertility hrough leaching. Phosphoric acid and potash are lost in small amount, but lime was found to be lost in considerable quantity, and this rapid loss to result in an acid soil condition.

Although quantitative generalisations cannot be made for soils of widely separated regions, one is justified in stating that, in any soil exposed to leaching, lime is the base which, as calcium bicarbonate, is most readily removed by leaching, and that at the other extreme, potash is the base which is least easily removed.

Assuming then, that the rocks that have given rise to the soils of Dominica are of practically uniform chemical composition, we may explain the considerable excess of lime present in the low-level soils of the leeward coastal belt, as compared with the soils of the upland region, and with those of the rainy windward coast to the greater amount of leaching that has gone on in the two last-mentioned regions. The relative amounts of magnesia, soda and potash present in these three types of soil are in accord with this conclusion.

Furthermore, it is perhaps reasonable tc assume, that a certain amount of the easily-leached bases, especially lime, present in the water draining off the high land, has been held up in some way in the leeward coast soils, and has thus augmented the supply of lime, magnesia and soda in them. Such retention would be less likely to occur in the windward coast soils where rain is more frequent, and where most of the drainage water is quickly carried to sea.

In support of this last theory, the following analyses of the water * draining away from the uplands in certain of the rivers of Dominica are presented:—

Constituents expressed as parts per 100,000.	Water-supply, Roseau.	In take of Reservoir, Roseau Valley.	Sweet River, where it leaves the forest.	Soufrière water-supply.
Total solids	16·4	17·6	16·0	31·5
Temporary hardness (calcium and magnesium bicarbonates chiefly) ..	3·0	3·1	3·2	7·8
Permanent hardness ...	nil	nil	nil	2·8
Sodium chloride ...	2·6	2·3	2·1	7·1

* Tempany. Dominica Bot. Sta. Ann. Report, 1915-16, p. 40-41.

These analyses indicate that leaching is still in progress in Dominica, and that the surface and drainage waters from the heights are still bringing down considerable amounts of base, some of which, especially in the valleys, might reasonably be expected to be retained by the low-level soils of the drier regions.

In this connexion Hilgard's conclusions drawn from the published results of an exhaustive soil survey of Madagascar are worthy of note. Hilgard writes * " It is apparent that lime and potash are extremely deficient in the soils of the mountain slopes of central and southern Madagascar, these substances having, as elsewhere in the humid region, been leached down into the valleys'.

As a result of excessive leaching, one would expect to find the soils of very rainy upland districts less alkaline then those of drier lowland districts, for the rapid removal of bases from rocks undergoing weathering would tend to deprive them of the substances that are responsible for the alkaline reaction. How far these remarks apply to Dominican soils will be indicated in Part II of this paper.

(C) *The mode of occurrence of calcium in the soils of Dominica.*

The analyses indicate that, whereas the total lime in the soils of the leeward coastal belt is considerably greater than in the soils of the upland regions, the amount of calcium carbonate present in these leeward soils is less than that in the upland soils. This would appear to imply that the leeward lowland soils contain calcium combined in some easily decomposed compound other than the carbonate, and that the upland soils do not contain the compound in any appreciable quantity. The nature of the unknown calcium compound has not been definitely determined. It may possibly be calcium silicate or even calcium aluminate formed by interaction of free aluminium salts in the soil solution of the lowland soils with calcium bicarbonate brought down by leaching from the uplands. Only additional analytical work after the method used by Shorey, Fry and Hazen [15] for example, could definitely establish its identity.

PART II. THE REACTION OF THE SOIL-TYPES OF DOMINICA.

The significance of the reaction of soils in relation to the fertility of those soils, has been reviewed in the introductory. It now becomes necessary to consider the question of the reaction of the several soil types of Dominica as outlined in the last section, and to find how far this has been decided by the origin and mode of formation of these soils, and to what extent it is related to their fertility.

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* Hilgard. E. W. "Soils" New York. Macmillan Co. 1918. p. 407.

(A) The Data Bearing on the Subject.

Several soil samples† were obtained from various estates on the leeward coast and in the upland region. No samples from the windward coastal belt could be taken at the time; their detailed study will have to be deferred to a future occasion.

The reaction of the soil samples collected were quantitatively estimated by the use of Gillespie's colorimetric method for determining hydrogen-ion concentration as described at page of the writer's article on soil sourness[6]. A certain number of determinations of the calcium carbonate content of several of the soil samples was also made. Marr's modification of Amos' method* was used. Finally the samples were tested as to their deficiency or otherwise in easily-soluble bases by Comber's method.°

The results obtained in these experiments, together with a certain number of data recorded by other workers, are set out in the following two tables (Tables II and III).

In connection with the reaction of the Dominican soils, an attempt is made in Table IV to find how far the reactions exhibited by soil samples of the regions surveyed may be correlated with the hydrolytic ratios of those soils. By 'hydrolytic ratio' is meant the ratio of the percentage of acid-soluble calcium and magnesium oxides, to the percentage of acid-soluble aluminum, iron and manganese oxides. Spurway[17] in a study of certain glacial soils of Michigan, found that there existed a definite relationship between the hydrolytic ratios of these soils and their reaction to litmus. Soils with the lowest hydrolytic ratio were found to be the most acid. The writer has applied Spurway's method of treatment of analytical results to the figures obtained by Watts[22]. The results obtained are set down in Table IV.

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† The soil samples were taken with a soil auger. Six cores were obtained at properly spaced points and united to form one sample. The top soils were taken to a depth of 1 foot, and subsoils, where specified, between the first and second foot.

* Marr: *Journ. Agr. Sci.* II. 1909, p. 155; Amos: *ibid.* I. 1905, p 322.

° Comber's test (*Journ. Agr. Sci.*, X. 1920, p. 420) depends on the fact that soils deficient in easily-soluble bases exchange ferric-ion for potassium-ion when an alcoholic solution of potassium thiocyanate is mixed with them, the test solution becoming blood red in colour when there is a deficiency of base in the soil under examination.

1. Soils of the Central Upland Region.

TABLE II.

Soil.	District.	Description of Soil.	Rainfall in inches.	Hydrogen-ion concn ; pH. values.	Percentage of calcium carbonate.	Deficiency or excess of easily sol. base (Comber's test).
I.	Saltoun. (16 acre plot	Top soil silty and black to 4″, whitish clay below.	200	4·4	0·020	Marked deficiency.
II.	Saltoun. (9 acre plot)	Top soil silty and black to 12″, reddish clay below to 24″, then white clay.	200	4·6	0·103	Deficiency.
III.	Saltoun. (Virgin forest)	Top soil silty and black to 20″, reddish clay below.	200	4·7	0·107	Deficiency.
XI.	Brantridge. (No. 19 plot)	Top soil silty and black to 6″, red clay below to 24″, then white clay.	230	4·9	0·037	Marked deficiency.
IX	Wotten Waven.	Rocky hillslope ; sandy black soil.	170	5·1	–	Marked deficiency.
X.	Wotton Waven.	Flat land ; sandy black soil with reddish clay below.	170	5·1	0·097	Marked deficiency.

The lime requirements of seven typical interior soils were determined by G. A. Jones* who used Hutchinson-McLennan method.† The result vary from 0·4 to 0·8 parts of calcium carbonate required to "correct the acidity" of 100 parts of soil. Jones noted that the forest soils were 'very acid in nature, especially when drainage is deficient owing to the close proximity of hard pan (solid rock) to the surface.'

It is especially worthy of mention that the *subsoil*, corresponding to the top soils tabulated above, in each case

* Annual Rept. Dominica Bot. Sta., 1916-17, p. 32 ; also recorded by Watts (24).

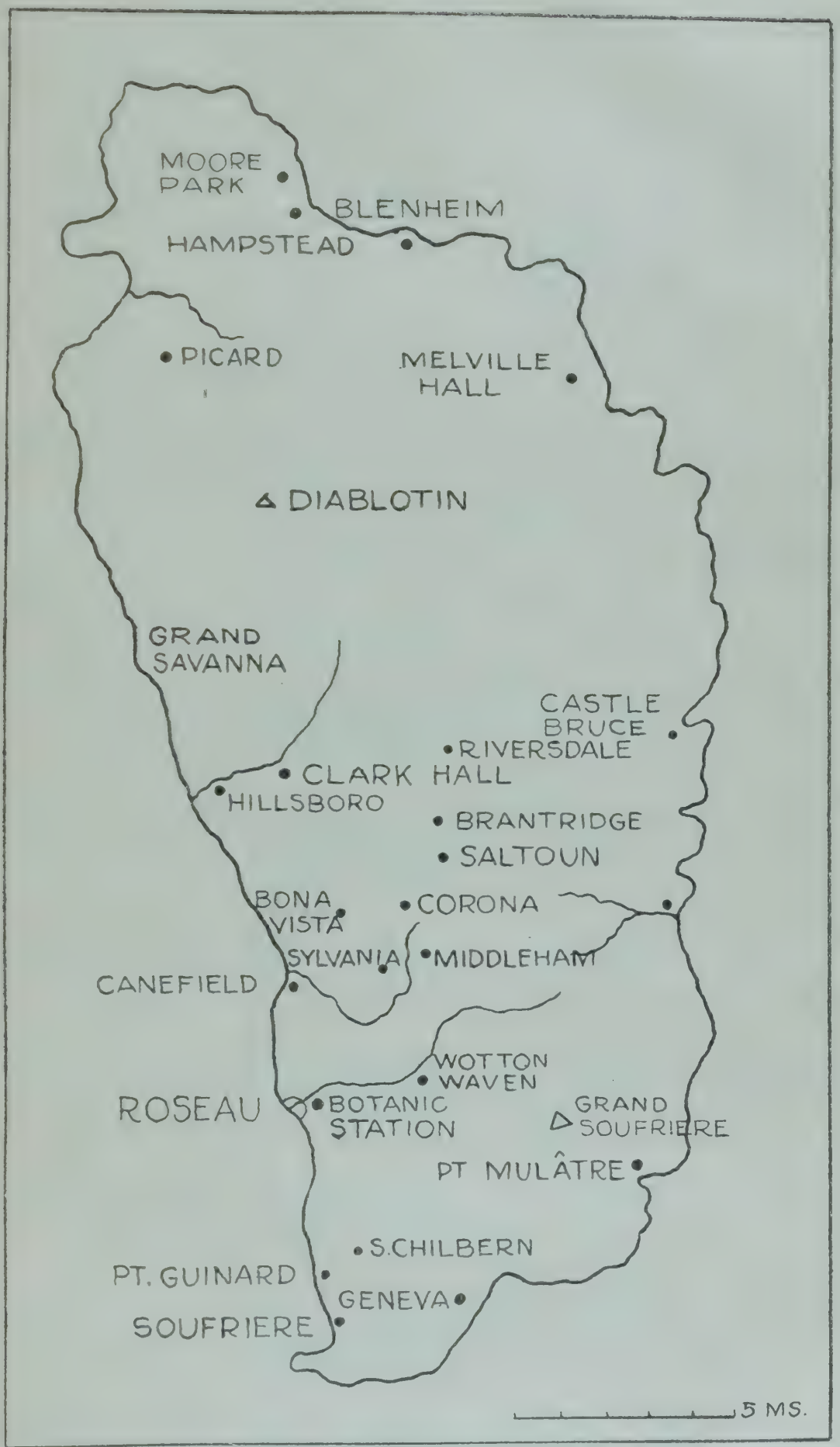
† *Journ. Ag. Sci.*, VII ,1915, p. 75.

gave a hydrogen-ion concentration (pH value) of the same number as that of the top soil, or differing from it by only 0·1. These results are, however, not recorded in the table.

3. Soils of the Leeward Coastal Belt.

TABLE III.

Soil.	District,	Description of Soil.	Rainlall in inches.	Hydrogen-ion concn; pH. values.	Percentage of calcium carbonate.	Deficiency or excess of easily sol. base (Comber's test).
	(*a*) *Hillside*	*soils.*				
XX.	Picard. (No. 13 plot)	Top soil clayey, subsoil reddish clay. Elevation about 500 feet.	90	5·1	–	Marked deficiency
XIX	Picard. (Blonchar)	Clay soil. Elevation about 800 feet.	100	5·6	–	Deficiency
XXII.	Soufriere.	Black sandy soil in pockets on stony hillside.	78	6·4	–	Neither
XII.	Pt. Guinard.	Ditto:	80	6·7	0·077	Excess
XVIII	Botanic Station. Lime plots.	Clayey soil receiving occasional mulch. Rocky hill slope.	80	6·8	–	Slight excess
XVI.	Canefield.	Top soil clayey and black to 8″. Red clay subsoil below.	74	7·0	0·037	Neither
XV.	Canefield.	Ditto:	74	7·4	–	Neither



SKETCH MAP OF DOMINICA.

3. Soils of the Leeward Coastal Belt.

TABLE III.—(*Concld.*)

Soil.	District.	Description of Soil.	Rainfall in inches.	Hydrogen-ion concn : pH. values.	Percentage of calcium carbonate.	Deficiency or excess of easily sol. base (Comber's test).
	b) Valley	*soils.*				
VI.	Clarke Hall.	Black silty alluvial soil.	100	6·4	0·030	Deficiency
IV.	Roseau, Bath.	Sandy soil on rocky flat near river.	80	6·5	–	Slight deficiency
XXI.	Soufriere.	Sandy black soil on stony flat land.	78	6·6	0·063	Neither
V.	Roseau, Bath near Emsall.	Sandy black soil on stony land at base of valley cliff.	80	6·7	0·080	Excess
VII.	Clarke Hall.	Black clayey alluvial soil with clay subsoil at 24 inches.	100	6·7	0·0043	Neither
XIV.	Canefield (Cacao bottom).	Sandy soil on recent alluvium.	74	6·8	0·023	Slight deficiency
XVII.	Picard.	Silty black soil with yellowish clay sub soil at 24″.	90	6·9	0·053	Slight deficiency
C	Botanic Station Cacao plots.	Sandy soil with gravelly subsoil.	78	7·0	0·081	Neither
VIII.	Hillsboro'.	Deep black silty soil of excellent tilth.	78	7·3	0·117	Considerable excess
XIII	Canefield.	Sandy soil on old alluvial flat. Stony subsoil.	74	7·9	0·160	Considerable excess

The lime requirements of a typical leeward coast soil (locality not stated) and of three soils of the Botanic Station were estimated by G A. Jones (*loc cit.*) The values are considerably lower than those obtained for the interior upland soils. They range between 0·025 and 0·175 parts of calcium carbonate per 100 parts of soil.

THE HYDROLYTIC RATIOS OF CERTAIN DOMINICAN SOILS.

TABLE IV.

Region of soil type.		$CaO + MgO$.	$Al_2O_3 + Fe_2O_3 + MnO$.	Hydrolytic Ratio. $\frac{CaO + MgO}{Al_2O_3 + Fe_2O_3 + MnO}$	Hydrogen-ion concn. pH values.
Central Uplands	Upper limit	0·30	23 19	1 : 77	
	Mean	*0·46*	*20·22*	*1 : 44*	4·8
	Lower limit	0·53	15·98	1 : 30	
Windward Coastal Belt	Upper limit	0·28	25·19	1 : 91	
	Mean	*0·41*	*22·24*	*1 : 54*	–
	Lower limit	0·84	22·97	1 : 27	
Leeward Coastal Belt	Upper limit	1·48	23·51	1 : 16	
	Mean	*1·58*	*15 06*	*1 : 9·5*	6·8
	Lower limit	2·41	10 64	1 : 4 5	

Note :—The hydrolytic ratios as set out in the above table are calculated from Watt's analytical data. The percentages of bases soluble in 20 per cent., hydrochloric acid were used in these calculations. Spurway (17) however used N/5 acid. The recorded pH values are the mean values of the results obtained by the writer for soils of the same regions as those dealt with by Watts, but the actual samples examined are not coincident therewith. Hence no exact correlation between the ratios and the pH mean values can be drawn. The pH figures are merely inserted to indicate the general agreement between the intensity of acidity of the soils of the three climatic regions as measured by the hydrolytic ratios and by the hydrogen-ion concentration.

(B) DISCUSSION OF THE DATA.

1. SOILS OF THE CENTRAL UPLAND REGION.

An inspection of the results set out in Table 11 indicates that the soils of the upland regions of high rainfall are markedly sour, for they all exhibit acid reactions towards indicators corresponding to a high concentration of hydrogen-ion ; are

notably deficient in easily-soluble bases ; contain low percentage amounts of carbonate, and have large lime-requirements. The hydrolytic ratios, as calculated from the composition of the acid extracts of the soils of this region, are characteristically high indicating also a markedly sour condition for these soils. Furthermore it is to be noted that the subsoils were found to be similar in reaction, and to possess in their soil solutions approximately the same hydrogen-ion concentration as the top soils corresponding to them.

There is evidently some potent acid-forming agent at work in these upland soils. The nature of soil acids in general has been described in the writer's article on soil sourness (6). It would appear from the list of acidic compounds tabulated at p. 45 of that article that in the the case of the upland soils of Dominica one would look for the acidic compound amongst the following substances.

(a) Alumino-silicic and silicic acids.

(b) Aluminium salts or salts of iron and manganese.

(c) Organic acids.

Only further detailed work could be hoped definitely to establish which of these is mainly responsible for the high, acidity of the upland soils.

A cursory inspection of the upland region would lead one to suppose that the almost permanently damp conditions that prevail there would be favourable to the accumulation in the soils of this region of organic waste products of an acid and toxic nature, and to suspect that oxidation is almost lacking in them. Although this may be true in many of the upland districts, especially in the clay-filled hollows, and in those places where sheet rock (locall known as hard-pan) immediately underlies the shallow surface soil, yet there are many localities where the natural drainage is fair. The mechanical soil-analyses reported by Watts [22] indicate that the majority of the upland soil samples examined by him were of a sandy or silty nature. One would expect such soils to occur on the sloping grounds of the uplands. The writer was able to confirm this by his own observations. Furthermore it was noted that the colour of the soil and subsoil in these better drained areas was of a bright red colour indicating that oxidation has gone on to a marked extent in them, for a red in soils is usually caused by the presence of iron in its most highly oxidized form.

There is one fact which is worthy of reiteration, in that it indicates the importance of mineral acids as distinct from purely organic acids as a major factor in deciding the reaction of many of the upland soils. It is the observation that, in all the soil samples examined, the subsoils exhibit the same degree of acidity as the top soils, and in some cases were even more acid than they. Specimens of pure red clay taken from a pit at a depth of four feet below ground level were also found to have as great intensity of acidity as the top soils, It is difficult to conceive how organic acids could be formed at these depths, or how they could penetrate so far below the soil surface so as to account for the acidity of these subsoils.

In conclusion it may tentatively be stated as a generalization that the main factor responsible for the acid reaction of the majority of the upland soils is either the presence of alumino-silicic acids or of hydrolizable salts of aluminium and iron. Possibly in the water-logged areas, where the soils are especially rich in humus washed down from surrounding sloping ground. the acidity may also in part be due to organic acids in the soil solution.

A detailed soil survey of the upland regions of Dominica would be necessary in order to establish the distribution of sour soils whose acdity is due to the various factors mentioned. Such a survey would appear to be the only method of defining the cause of sourness in any particular locality.

2. SOILS OF THE WINDWARD COASTAL BELT.

As has already been mentioned, the soils of this region have not as yet been examined as to the hydrogen-ion concentration of their soil solutions. The general chemical characteristics of the soils (tables I and IV) indicate, however, that they differ but little from the upland soils, and to some extent may be considered as being intermediate between these upland soils and the soils of the leeward coastal belt. They apparently show considerable variation amongst themselves, however, and a detailed investigation might lead to interesting revelations in connexion with their genesis and fertilty.

3. SOILS OF THE LEEWARD COASTAL BELT.

The experimental data set out in Table III indicate that the soils of leeward coastal belt of comparatively low rainfall are on the whole approximately neutral in reaction. Neutrality is represented by a pH value of 7·0, and the typical reaction of these soils lies between pH 6·4 and 7·4 having an average value of something near 6 8. The soils, however, do not contain appreciable excess of calcium carbonate. It must be borne in mind that the lowland soils are probably receiving constant additions of calcium carbonate leached out of the upland soils, and this may prevent their carbonate content from falling dangerously low. Apparently, from Comber's test, there is only in a few cases a deficiency of easily soluble base in these soils, and their lime requirements are either negative or low. The hydrolytic ratios of the leeward soils are very small, and in this characteristic they stand out in marked contrast to the soils of the other two climatic regions.

The data would appear to fall into two groups, and to indicate the subdivision of the leeward soils into hillside soils and valley soils. (Table III.) The former, on the whole, are more acidic in reaction and more deficient in easily-soluble bases than the latter. These differences may be assigned to the greater leaching action to which the hillside soils have been and are subjected.

PART III. THE CORRELATION OF REACTION AND FERTILITY IN CERTAIN CACAO AND LIME SOILS OF DOMINICA.

In order to find out how far the reaction of the Dominican soils growing cacao and lime trees can be correlated with the productivity of these soils, an investigation into the growth conditions presented by the experiment plots of the Roseau Botanic Station was undertaken. The results of this investigation are applied to other cases of cultivated soils of the leeward coastal region, to discover whether or no those relationships between reaction and fertility which apparently hold in the case of the Botanic Station plots, are capable of broader application in Dominica. A similar attempt is made in connection with the soils of the upland regions. The soils of the windward coastal belt were not studied.

It would be advisable to consider these various areas in the order indicated.

(A) The Experiment Plots of the Botanic Station.

The area occupied by the Dominica Botanic Station exists on the site of an old river bed or alluvial flat which is now elevated somewhat above the level of the present river owing possibly to earth uplift with which however, the river has kept pace by deepening its present valley.

The soil of the Station, especially along the base of Morns Bruce, is a sandy loam of an average depth of three or four feet.

On the whole, it does not differ greatly, at least as far as geological origin and mineralogical composition are concerned, from the soil of the neighbouring parts of the Roseau valley, of indeed from that of the lower parts of many similar valleys or the leeward coastal belt of Dominica.

1. THE CACAO PLOTS.

The land set aside for the manurial experiments with cacao at the Botanic Station includes three main series of plots which have been laid down at various times. They may be described as follows.

(i) The *original series* of five plots (A to E) laid down in 1900 on land bearing cacao trees of age ten years.

(ii) The *additional series* of four plots arranged in two sets i. e.

(a) Plots F and G which form an extensive of the original series, and

(b) Plots H and I which are laid out on the steeep slopes of Morne Bruce bordering the last two plots.

These four plots were inaugurated in 1907.

(iii) The *new series* of two plots K and L, laid out in 1913, on the hillside in the vicinity of the plots H and L.

The hillside plots H, I, K and L were intended to test the effects of certain treatments found to be beneficial by the results

of the original series of trials, on cacao planted under conditions which are typical of much of the cacao land of Dominica.

The manurial treatments and the results obtained in the trials, together with the detailed history of the experiments, are, fully described and discussed in the Annual Reports of the Dominica Botanic Station and in various numbers of the *West Indian Bulletin*.[4], [2], [18]. The necessary details for the purpose of the present article are contained in the following table, (Table V.)

CACAO PLOTS.

Designation of plot.	Manurial treatment.	Average annual yield in lb. per acre of cured cocoa calculated up to 1920.	Percentage increase in yield over no manure plot.
(i) A.	Phosphate (basic slag and potash).	1430 lb.	25·3±2·5*
B.	Organic nitrogen (dried blood).	1396 lb.	22·3±2·6
C.	Control (no manure)	1141 lb.	——
D.	Vegetable mulch.	1763 lb.	54·5±1·6
E.	Complete manure.	1633 lb.	43·1±1·9
(ii) F.	Vegetable mulch.	2060 lb.	138·5±1·9
G.	Organic nitrogen (Cotton seed meal).	1653 lb.	91·4±1·2
H.	Control (no manure)	863 lb.	——
I.	Vegetable mulch.	1558 lb.	80·0±1·9
(iii) K.	Vegetable mulch + Lime.	1003 lb	16·2
L.	Nitrolim replaced, after one year by cotton seed meal.	1280 lb.	48·3

The physical properties of the soils of the different plots have been described by Tempany[18] as follows. 'The soil of the plots A to G is of a distinctly light and sandy nature but tends to become heavy on plots D and E which are at a slightly lower level than the other plots. The soil of the hillside plots is similar in texture to that of D and E. The subsoil forms a continuation of the top soils and presents a considerable thickness of coarse sands and gravels through which water percolates freely. During the rainy season the water-table usually stands about eight feet below the surface of the ground; . . . . . the subsoil water supply is augmented by drainage from the slopes of Morne Bruce." (ibid p. 84).

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* The probable errors given in this column are those calculated by Tempany. (18.) The yield figures have been criticised by Dunlop (14) and defended by Jones (12.) Probably the percentage increases as tabulated are somewhat high, but on statistical grounds it may be conceded that the cacao crop can definitely be expected to benefit from manurial treatment with vegetable mulch, and to a lesser degree by the use of a complete manure.

The chemical composition of the soils of the plots calls for no special comment. It approximates closely to that of an average lowland valley soil as stated in Table I (p. 96).

Tempany's analytical data[18] indicate the magnitude of the gains and losses that have gone on in the soils of the various plots as regards plant nutrients originally present and added as manures, or removed by the plants. In particular, the data, along with further facts brought to light by another investigation[19] show that nitrogen-fixation by bacteria of the *Azotobacter* type is conspicuously active in the soil of the majority of the plots, more especially those that have received vegetable mulch. Tempany specially comments on this high degree of bacterial activity, not only in connection with nitrogen-fixation, but also with regard to the rapid destruction of humus in many tropical soils, and states that the discovery is somewhat unexpected in view of the small content of calcium carbonate of most of the soils, as for example, those of the experiment plots under investigation. He accepts a suggestion made by Watts that "under conditions in which the supply of free mineral bases in the soil is deficient, ammonia formed in the process of ammonification may function as a base for the neutralization of nitric acid formed during the later stages of nitrification.' ([18], p. 105; [19], p. 151). We shall have need to refer to this statement later.

The cacao trees occupying the manurial trial plots are, on the whole, in a healthy condition, and yield crops which are considered very high for Dominica. Hence we may assume that the environmental conditions for growth at the Botanic Station are eminently satisfactory as far as the cacao plant is concerned.

The following data which have bearing on the reaction of the soils as one of the factors involved in the growth of cacao, have been brought together from published figures and from the records made by the writer during his own investigations in Dominica.

Cacao Plots.

TABLE VI.

Plot.		Manurial Treatment.	Hydrogen-ion concn. pH values.	Percentage of Calcium carbonate.	Lime requirement ($CaCO_3$ per 100 parts of soil).	Deficiency or excess of base. (Comber's test)
Plots on the flat						
1900						
A	Top	Phosphate (basic slag)	7·1	0·124*	...	Excess
	Sub	+ Potash.	7·1	...	...	
B	Top	Organic nitrogen	6·7	0·104*	...	Neither
	Sub	(dried blood).	6·9	...	...	
C	Top	No manure	7·0	0·100*0·081	0·025†	Neither
	Sub		7 1	...	...	
D	Top	Mulch	6 9	0·112*0·107	0·037†	Neither
	Sub		7·1	...	...	
E	Top	Complete manure	7·1	0·104*	...	Neither
	Sub		7·2	...	...	
1907						
F	Top	Mulch	7·0	...	...	
	Sub		7 0	...	...	Neither
G	Top	Organic nitrogen	7·0	...	...	Neither
	Sub	(Cotton seed meal).	7·0	...	..	
Hillside plots						
H	Top	No manure	6·9	...	...	Neither
	Sub		6·9	...	...	
I	Top	Mulch	6·8	...	...	Excess
	Sub		7·0	...	...	
1913						
K	Top	Mulch + Lime (5 cwt)	7·4	0·840	...	Considerable excess
	Sub		7·5	...	...	
L	Top	Nitrolim and organic nitrogen	7·1	...	...	Excess
	Sub	(Cotton seed meal).	6·9	...	...	

*As determined by Tempany in 1915 (19, p. 93); Watts's method was used (22, p. 30).

†As determined by G. A. Jones and recorded by Watts (24, p. 335). The methods used in the determinations were the same as those previously mentiond in this article.

The following conclusions may be drawn from these data.

1. The soil of the plots in the majority of cases possesses a slightly alkaline or neutral reaction. Especially is this fact noticeable in the case of the flat land plots, A to G. Generally speaking, the reactions can be positively correlated with the calcium carbonate content of the soils: It would appear from analyses performed in 1902 (Watts,[22], p. 2), 1915 (Tempany [18], p. 93) and 1920 (by the writer), that the average calcium carbonate content has for many years remained almost constant and at a figure of approximately 0·10 per cent During the past twenty years much calcium must have been removed from the soil by the trees during growth, in the cacao pods which have been harvested, and in calcium nitrate etc. in the drainage water from the plots. The soil does not seem to contain a sufficient reserve of calcium-bearing minerals to maintain the supply of calcium carbonate, for the 1902 analyses [22] indicate that the *total* calcium oxide content of the soil was then of the order 1·2 per cent, which is relatively low. Unfortunately no further estimations of total calcium oxide have been made in more recent years, so that one cannot draw exact comparisons between calcium carbonate content and calcium oxide content for the years subsequent to 1902. It appears highly probable, however, that extra supplies of calcium compounds have been introduced into the soil of the plots from some outside source, and that the most likely source has been and is the drainage water which runs down the slopes of Morne Bruce which borders the plots on the eastern side. This theory has already been advanced in an attempt to explain the reason why the lowland leeward soils in general have a lower acidity than those of the uplands.

The question of the rate of wastage of calcium compounds in the soil is not, however, so simple as it would at first sight appear to be. In certain cases calcium compounds are brought up in the water which moves upwards from the subsoil into the top soil owing to the operation of certain physical forces that are especially manifest in soils of high clay and humus content.

Further, Coville's experiments [3] on the formation of leaf mould indicate that deep-rooted plants can bring about an increase in the total calcium content of the top soil by the fact that their roots extract calcium from the lower soil layers and return it to the top soil in the debris which accumulates on the decay of their fallen leaves. Actual chemical analyses have shown that such a process does go on in many soils that support prolific plant growth.

These two agencies for increasing the calcium content of surface soils have probably not been very positive in their effect in the case of the cacao soils under consideration. Firstly, these particular soils are of a sandy texture and their water table seldom rises above a depth of eight feet from the ground level even in the rainy season, so that upward movement of water in them is restricted. Secondly, the root system of the cacao plant is not markedly deep-feeding, and probably therefore removes but little nutriant material from the subsoil.

In the absence of further definite experimental data one would perhaps be justified in concluding therefore that the leach-

ing of calcium compounds from the weathered rock of the elevated land that borders the cacao plots maintains a supply of calcium in the soil of these plots sufficient to meet the demand of the cacao trees, and of the reactions that go on in the soil. There would thus appear to be no need to invoke a theory based on the supposition that ammonia liberated in ammonification serves as a base to neutralize acids produced during nitrification to explain the apparently unrestrained activity of nitrifying bacteria in the soil of the cacao plots, as has been done by Tempany (see p. 109).

2. The effects of the manurial treatments on the reaction of the soil solutions of the various plots are clearly shown by the figures for the pH values. Chemical fertilizers have had little or no effect on the reaction, but organic manures have apparently reduced the alkalinity somewhat, especially in the original series of trials (B and D) which have received manurial treatment for twenty successive years.

Numerous investigations have shown that in general organic matter in well aerated soils does not tend markedly to induce an acid reaction (see [6], p 77). Except under conditions of water logging, any acidity that is produced by decaying organic matter is in most cases chiefly due to carbonic acid (*ibid.* p. 46). Mulching in the cacao plots seems to have resulted in a slight augumentation of the calcium carbonate content which is in accordance with the statements made in the last section in connection with the calcium content of leaf-débris.

3. The addition of lime in the form of a small dressing of slaked lime to plot K has resulted in a comparatively large increase in alkalinity. The magnitude of this increase considered in relation to the smallness of the dressing of lime, points to a lack of buffer action (see [6], p. 57) in the soils.

The two soils for which lime requirements have been determined (i. e. C and D) indicate that a greater correlation exists between the pH value and the amount of lime required to correct acidity than between the total carbonate and the lime requirement, for the greater the intensity of acidity in the soil solution, the greater is the lime requirement of these two soils. We have, in fact, in the two soils C and D what is referred to by (Watts [24], p. 337) as 'a curious situation; the so-called acid soils contain carbonates and still are able to neutralize or absorb further quantities of carbonate of lime.' This possibility is not, however, opposed to the results of investigations on acid soils of other regions. It has been fully discussed elsewhere (see [6] 66), to which article the reader is referred for further information.

2. THE LIME PLOTS.

A series of manurial experiments with limes was laid out in 1913 in a narrow valley beyond Morne Bruce and bordering its southern side. Part of the cultivated land had been planted with limes in 1893, but had been allowed to run into bush. Unfortunately the hurricane of 1916 caused so much damage to the trees that the whole series of experiments had to be reorganised and the plots in part replanted.

As at present constituted, the plots are arranged in three series or groups of five plots. Each plot in a series receives a different manurial treatment, so that each treatment is repeated three times. The plots run parallel to each other down the valley and are successively numbered 1, 2, 3, to 15.

Series I. (plots 1 to 5) occurs at the upper end of the valley on land which was originally under garden cultivation, but which at the time of planting the lime trees (in 1913) was in a very bad state. Thorough weeding, followed in 1915 by draining, forking, and the application of small dressings of lime and of organic manure brought the trees into a sound condition. Artificial wind breaks form a necessary protection to the lime trees in this exposed part of the valley,

Series II. (plots 6 to 10) is situated lower down the valley and at its middle portion. It resembles the last in situation and preliminary cultural treatment. The majority of the trees were planted in 1913.

Series III. (plots 11 to 15) includes much of the original land which was planted with limes in 1893. The plots occupy sloping ground which is typical of large areas of lime cultivation in Dominica.

Two other unduplicated plots occur adjoining the last series. These may be designated plots 16 (F) and 17 (G). In addition, a large area of land under old lime cultivation occupies the steep slope to the west of Series III. It is not systematically manured however, but receives occasional dressings of vegetable matter. It may be designated plot 18.

The history of the plots and the cultural and manurial treatments to which they have been subjected are fully described in the Annual Reports of the Dominica Botanic Station (1912-20). It is perhaps scarcely legitimate to draw conclusions from the insufficient data so far obtained in the experiments after they were recast in 1916, or to criticise the yield figures on statistical grounds. The following table (Table VI) is sufficient to indicate the tendency of the yield figures and of the productivity of the trees under the conditions of growth presented to them

LIME PLOTS. TABLE VII.

Plot.	Manurial Treatment.	Average annual yield of triplicate series in barrels of limes per acre, for season ending March 1920.	Percentage increase in yield over no-manure plot.
A.	Complete manure.	311 barrels	33·5
B.	Control (no manure)-	233 ,	—
C.	Vegetable mulch.	268 „	15·0
D.	Organic nitrogen (tankage) and phosphate (basic slag).	284 „	23·2
E.	Organic nitrogen (tankage) and potash.	243 „	4·3
16 (F)	Organic nitrogen (cotton seed meal).	—	—
17 (G)	Vegetable mulch and lime	—	—
18	Occasional mulch.	—	—

The yield figures are very high for the lime crop in Dominica where yields of over 200 barrels to the acre are considered good.

Unfortunately no systematic laboratory examination of the soils of the lime plots has been recorded. The following general description of the soils is taken from the Annual Report for 1919-20 as drawn up by Mr. Joseph Jones.

'The upper part of the valley now under bearing limes is formed of both steep and easy sloping land; the middle is mainly composed of steep hillsides with a shallow soil, and the lower part (where new trial plots are soon to be laid down) is a little less steep. There are no flat lands.' The soil had been ill-used previously to the inauguration of the experiments in 1913. It had been 'exhausted by peasants' garden crops, baked by the sun, washed by heavy rains and swept by wind.' Subsequent treatment, however, has made the soil highly productive, and 'there appears to be no reason why the soil of this valley should not in time become one of the most fertile spots in the island.'

It may therefore be assumed that at the present day the environmental conditions for growth at the Lime Experiment Station are satisfactory as far as the lime plant is concerned.

During the investigation carried out by the writer, samples of the soils of the lime plots in Series III, Nos. 11 to 18, were taken and the determinations recorded in the following table were made on them after air-drying.

The following conclusions may be drawn from the results set out in Table VII.

LIME PLOTS. TABLE VIII.

Plot.		Soil type.	Manurial treatment.	Hydrogen-ion concn. pH values.	Percentage of calcium carbonate.	Lime requirement. ($CaCO_3$ per 100 parts of soil).	Deficiency or excess of base (Comber's test).
11 (A)	Top	Sandy loam	Complete manure.	6·8	.....	.....	Excess
	Sub			6·8	.....	.....	
12 (B)	Top	Sandy loam	No manure.	6·6	0·033	0·175*	Neither
	Sub			6·6	.....	.....	
13 (C)	Top	Sandy loam	Mulch.	6·5	.....	.....	Slight
	Sub			6·6	.....	.....	deficiency
14 (D)	Top	Clayey loam	Organic nitrogen + phosphate	6·4	.....	.....	Slight deficiency
	Sub		(basic slag)	6·7	.....	.....	
15 (E)	Top	Clayey loam	Organic nitrogen	6·5	.....	.....	Neither
	Sub		+ potash.	6·6	.....	.....	
16 (F)	Top	Clay soil	Organic nitrogen (cotton seed meal).	6·7	.....	.....	Neither
	Sub			6·8	.....	.....	
17 (G)	Top	Clay soil	Mulch + lime.	7·1	.....	.....	Slight
	Sub			7·1	.....	.....	excess
18	Top	Clay soil	Occasional mulch.	6·8	.....	.....	Slight
	Sub			7·0	.....	.....	deficiency

*As determined by G. A. Jones and recorded by Watts (24, p. 335).

1. The soil of all the plots except 17 (G), which receives lime, possesses a slightly acid reaction. There is a slight deficiency of lime in most cases. Appreciable leaching of calcium compounds has apparently gone on, and this can partly be explained by the position of the plots situated as they are on the sides and sloping base of a steep valley.

2. The effects of the manurial treatments on the reaction of the soils are fairly clearly shown. The complete manure, by reason of its content of basic slag, has apparently raised the pH value of the soil solution of plot 11. Mulching has resulted in a slight increase in acidity in each case. Probably the rather large effects in these cases are due to a lack of inorganic buffers in the soils of the lime plots, as in the case of cacao plots last considered.

3. The intensity of acidity in the soils of the plots is apparently not sufficiently large markedly to affect the growth of the lime trees.

(B) OTHER LEEWARD COASTAL DISTRICTS WHERE CACAO AND LIMES ARE GROWN.

It is a noteworthy fact that in the various districts of the leeward coastal region where cacao and limes are grown that the general correlation between high productivity and soil reaction found to hold in the case of the experimental plots of the Botanic Station also applies in those districts that were examined. Thus the best *cacao* soils were found to have a reaction which is approximately neutral, for example Hillsboro (VIII), pH = 7·3; Canefield (XIV), pH = 6·8; Bath (V), pH = 6·7; Pt. Guinard (XII) pH = 6·7, whereas *limes* are apparently growing well on soils of more acid reaction, for example, Bath (IV) pH = 6·5; Soufriere (XXI), pH = 6·4; Clarke Hall (VI) pH = 6·4; Picard (XIX), pH = 5 6.

It would be quite illogical to conclude from these scanty observations that a strict positive correlation exists between the growth of cacao and of limes and soil reaction, for soil reaction is but one of many factors which influence the growth of these plants. It has been shown that there is some relation between tilth and the growth of the cacao tree ([1],[20]). Whether tilth and soil reaction in this case are themselves definitely related yet remains to be proved, and an interesting problem arises out of this coincidence.

(C). THE UPLAND DISTRICTS.

The fertility of the soils of the rainy upland region of Dominica has been discussed in certain publications to which reference has already been made in this paper ([3],[21], [23]). The luxuriance of the forest vegetation in this region has led to the commonly accepted view that the forest soils are exceptionally fertile. In this connexion the remarks of Professor J. B. Harrison in a report on the forest soils of British Guiana are

worthy of careful note. Professor Harrison writes* "The question has been raised as to how it is possible for the British Guiana soils if they are so lacking in fertility, as appears from analyses, to support as they do a heavy forest growth. In the case of a forest, the nutrient constituents of plant food are taken up by roots which traverse a very wide area ; in that of cultivated plants, the space occupied by the roots is comparatively small ; hence the trees can draw their necessary food from a relatively enormous mass of soil compared to that which the cultivated plants can utilize. The mineral constituents, in the case of the trees, accumulate in the leaves and in the small branchlets, but little being retained in the wood of the stem, and, when the leaves are shed, are in a great part returned to the soil. Similarly, a considerable proportion of the plant food is, in the case of certain trees, returned by the fallen flowers. The plant food thus returned to the soils from which it is derived is set free by the decomposition of the leaves etc., and is again utilized by the trees. Thus the plant food present in the forest soils may be described as circulating and performing its functions in a practically endless circuit from soil through the tree to its leaves and flowers, and, with its leaves and flowers, to the soil. The tendency in the forest is for much of the plant food gathered by the deeper roots to accumulate in the upper layers of the soil In our tropical forests this has taken place in the course of ages to such an extent that the trees which now flourish therein are largely surface feeders so that their roots spread through the thin layers of vegetable débris on the surface soil in a wide extending plexus."

"With the majority of cultivated plants the constituents of the manurial plant food are largely removed in the products, and are thus lost to future generations of plants raised on the same soil. Hence soils capable of supporting a long continued forest growth may, and, as repeated experience here during recent years has amply proved, do, when under economic cultivation, fail after very few seasons to produce crops of any value."

"Further, forest soils appear in many cases to flourish on soil solutions of far lower saline contents than the majority of plants of economic value can do, and it is a matter of interest to plant physiologists to ascertain if this power of assimilating soil solutions of greater diluteness may not be due to the trees growing in symbosis with some of the fungoid organisms with which the upper layers of our forest soils teem."

Professor Harrison has raised many points of interest by these remarks. Of special importance is the composition, concentration and reaction of the soil solutions of tropical soils. Whereas most of the virgin soils as exemplified, for instance, by the soils of the rainy regions of Dominica, are generally not very rich in the so-called reserves of plant nutrients, it must be borne in mind that it is the actual composition of the soil solution and

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* J B Harrison Report on Agricultural work for 1902 British Guiana. Pt, II, p, 49

not that of the soil itself that is of immediate importance in plant nourishment. The minerals in a soil yield various substances to the soil water, and these are either absorbed by plant roots or leached out in the drainage water. The processes of solution and absorbtion are essentially dynamic and the relative *rates* at which they proceed decides the ability of a soil to maintain a supply of nutrients to the plants it supports.

As Hilgard points out,* it is possible that, under tropical conditions of high rainfall, the rate of decomposition and solution of the mineral nutrients in rocks is so much more rapid than in temperate countries that a soil which, by the usual methods of chemical analysis, appears to be lacking in nutrients may really be highly productive; this of course provided the other numerous factors governing plant growth are favourable.

The question of the calcium supply of plants growing in tropical rain forests is of especial interest. Calcium-ions are absorbed by plant roots and function in some way in precipitating and neutralizing the acidic waste products of metobolism in the plant sap. Each species of plant apparently has its own lime requirement (see [6], p. 68). In regions of high rainfall leaching rapidly removes soluble calcium compounds but plant roots at the same time are competing with it for calcium. In accordance with the dynamic conception of the relation between the soil environment and the plant, it thus becomes apparent that a soil, showing little calcium content when chemically analysed according to the usually accepted conventions, may yet supply the needs of certain plants as far as calcium is concerned. It is possible, however, that only plants of low lime requirements could produce satisfactory growth in soils subjected to excessive leaching. Thus we have here an ecological relationship which may in some measure decide the kind of plant that can thrive in very rainy districts.

The relative unimportance of soil acidity *per se* as a factor in plant growth has been pointed out in the introductory. Unless the hydrogen ion concentration of the soil solution is greater than that represented by a pH value of about 5·0, normal bacteriological processes that ensure a satisfactory nitrogen supply to most plants can go on more or less unchecked in a soil. The acidity of forest soils is, however, frequently much greater than the approximate lower limit stated above. In the upland forest soils of Dominica it has a mean value of about pH 4·6 as indicated by the writer's observations. (Table II). Such a high degree of acidity would be expected to exercise a marked suppression of the activities of bacteria of nitrification and nitrogen-fixation, unless indeed special acid-resisting strains of the bacteria can exist in soils, which would appear unlikely (5). The question of the nitrogen supply of plants growing in acid forest soils is not as far as the writer is aware, yet thoroughly understood. The possibility of ammonium salts serving as the direct nitrogenous food material of plants growing in highly acid soils may furnish an explanation of the difficulty. The bacteria of ammonification can apparently withstand a much greater intensity of

*"Soils." Hilgard, p. 410.

acidity than can the bacteria of nitrification and nitrogen-fixation, so that the production of easily assimilable ammonium compounds from plant residues probably goes on quite rapidly in highly acid soils.

The possibility of the occurrence of mycorhiza growing in symbiosis with the roots of plants that thrive in acid soils must not be overlooked. Their activity does not require that nitrates be present in the soil, for they are apparently able to absorb nitrogenous compounds of some complexity and to pass on elaborated nitrogenous food material to the host plant that harbours them,*

The success of cultivated plants such as the lime tree and cacao that are introduced into newly-opened forest soils may therefore depend either on the ability of these plants to obtain their necessary supply of nitrogen under the peculiar conditions in which assimilable nitrogenous compounds are formed in such soils, or on the degree to which deforested soils can alter under the effects of cultural treatment. The question of the bacteriological content in relation to nitrogen transformation in acid forest soils, and the occurrence or otherwise of mycorhiza on the roots of natural forest plants and on those of plants that are able to adapt themselves to forest soil conditions, would seem to be of special importance in connexion with the development of newly opened forest lands in the tropics. There would appear to be a pressing need for field experiments designed to test the ability of lime trees, etc., to assimilate various forms of nitrogenous food materials. Already there is some indication that ammonium salts stimulate the lime tree to increased activity.

Both the lime tree and the cacao tree possess widely-spreading surface feeding root systems. This would appear to enable them to obtain a sufficient supply of mineral nutrients when growing in soils subjected to considerable leaching.

Furthermore, much evidence has accumulated to indicate that the presence of a thick layer of vegetable mulch on the soil surface is greatly beneficial to their growth (see p. 108). Exactly why this is so has not yet been explained. Newly opened forest lands characteristically possess a large amount of humus which occurs chiefly as a layer of leaf mould on the soil surface.

When these soils are exposed to the action of rain, erosion rapidly ensues and the humus layer is quickly removed. Unless humus is replaced by artificial mulch, one the chief advantages of fresh forest soil is lost, and another inhibiting factor, besides those already enumerated, is introduced.

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*McLean (13) in his studies of the tropical rain forests of South Brazil, noted that the soil of these forests is shallow and pervious, with a water holding capacity of about 40 per cent. and an average water content of 10 per cent. It is deficient in mineral nutrient material, particularly in calcium carbonate. The humus content is about 3 per cent. Mycorhiza is abundantly developed on the roots of the forest trees.

Hesselman (10) has shown that certain types of humus soils formed in Swedish forests are low in mineral nutrients, and exhibit little or no nitrate formation. He concludes that plants growing in such soils must be capable of assimilating nitrogen in the form of ammonium compounds.

Hutchinson and Millar (11) have discussed the general question of the absorption by plant roots of ammonium compounds.

The possibility of the presence of toxic amounts of aluminium etc., in the soil solution of the upland soils of Dominica has been alluded to in the discussion of the source of the acidity of these soils. Exactly how far aluminium etc., may act as a limiting factor in the growth of plants in the upland region is not known Nor has the effect which the possible presence of organic toxins exerts on the productivity of these soils yet been fully appreciated. That all these and many other factors should be accurately gauged before any definite opinion is expressed as to the economic possibilities that might follow on the development of the forest areas of Dominica, and indeed of similar areas in certain others of the West Indian Islands would appear to be self evident.

With regard to the particular question of lime cultition in the upland region of Dominica, the experience of planters who are struggling with the difficult conditions that exist there, and the teachings of the valuable data obtained in the plot experiments of the Roseau Botanic Station would seem to indicate that the lime plant flourishes best in soil which is not too acidic, and which contains appreciable amounts of lime. The drainage question in successful lime cultivation is perhaps of greater importance than either of these two factors, but it is intimately bound up with soil aeration, which has been shown in turn to bear a direct relation to acidity and to the formation of toxic organic compounds in the soil.

Finally the incidence and spread of certain fungus diseases in the soil of the upland region and their menace to lime cultivation have been studied in some detail by mycologists attached to the Imperial Department of Agriculture. (see especially Nowell, 3). An acid medium in the majority of cases favours the spread of certain fungi. Any condition which brings about a decrease in soil acidity may be expected in general to reduce disease due to fungi (for example *Rosellinia*), which normally live in soil but which can, under certain conditions, attack living plants. Nowell recommends liming (loc. cit. p. 33), for this reason. Thorough drainage, which increases aeration is also recommended. This would accelerate the destruction of organic substances upon which certain fungi feed in the soil.

Liming to ameliorate the conditions in the Dominica upland region soils is an expensive operation owing chiefly to difficulties of transport. The writer wonders whether or not the finely comminuted volcanic ash (terrace or tarris), found in abundance in most upland districts of Dominica and easy to quarry would not serve a useful purpose in forest soil cultivation. Such material contains a considerable amount of calcium in the form of complex silicates. Under the conditions of rapid weathering which occur in rainy regions, these silicates are undoubtedly quickly decomposed and their calcium rendered available for certain soil reactions that may result in improved conditions for growth. Hartwell and Pember* at the Rhode Island Agricultural Station have recently shown that calcium

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* *Soil Science X, 1920, p. 57.*

silicate (Ca_2SiO_4) is able to precipitate active aluminium in soi solutions where this element occurs in toxic amount. Possibly natural calcium silicate minerals, such as occur in tarris might have a similar effect, and trials as to its value as an ameliorant for upland forest soils would thus appear for this additional reason to be greatly desirable.

SUMMARY.

1. The soils of Dominica have been derived from volcanic rocks (lavas, breccias and tuffs) of which the island is mainly composed.

2. These volcanic rocks, as far as is known, consist chiefly of hypersthene andesite and its fragmental equivalents.

3. Grains of minerals such as plagioclase felspars, ferromagnesian minerals and certain accessary and secondary minerals, have been identified in the soils of Dominica. They have been derived from the volcanic rocks by processes of disintegration, weathering and transportation.

4. The variations in the rainfall of the different topographical regions of Dominica have given rise to three main soil types which may be designated (1) Soils of the Central Uplands, (2) Soils of the Windward Coastal Belt and (3) Soils of the Leeward Coastal Belt. The chief chemical characteristics of these soil types are summarized in the text.

5. Lateritization, due mainly to excessive leaching, has apparently gone on to a considerable extent in the wetter districts of Dominica.

6 The Central Upland soils are markedly acid in reaction, owing possibly to leaching which has resulted in an accumulation of alumino-silicic and silicic acids in the soils, together with the formation of soluble salts of aluminum etc. Coupled with this is the possible presence of organic acids in the more water logged and highly humic soils of the upland region.

7. The Leeward soils are approximat ely neutral in reaction

8. The Windward soils are somewhat intermediate in type.

9. The cultivated soils of the Leeward Coastal Belt are highly fertile to the growth of cacao and limes. Their general characteristics have been studied in some detail, especially in the cacao and lime experimental plots of the Roseau Botanic Station, where the general effect of manurial treatment on the reaction of the soil has been investigated.

10. The soils of the Upland region are pre-eminently interesting because of the luxuriance of the forest vegetation which they support, suggesting as it does an apparent high degree of fertility in these soils. A consideration of the factors which operate in deciding the main features of such forest soils indicates certain peculiar conditions which might not in all cases be favourable to the successful cultivation of plants such as limes and cacao. A complete study of forest soil conditions would appear to be of economic importance in connection with the agricultural development in Dominica and in certain other West Indian islands, of such upland regions of high rainfall.

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THE ECOLOGICAL SIGNIFICANCE OF SOIL SHRINKAGE *

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Statement of The Problem.

A good general correlation was found by Sir Francis Watts [22] to exist in certain valleys of Dominica, between the percentage linear shrinkage of the soil on air drying and the condition of cacao rooted in it; relatively large shrinkages were in general accompanied by the failure of the cacao. It was primarily with the object of ascertaining the ecological significance of this relationship, and secondarily in the hope that some principle of wider application might emerge from the investigation, that the work reported in this paper was undertaken

Introduction.

The employment of soil shrinkage determinations as an index to soil texture, was initiated by Sir Francis Watts, while Government Chemist and Superintendent of Agriculture of the Leeward Islands. It was thought, Auchinleck [1] states, that by measuring the shrinkage upon drying experienced by masses of soil of similar plasticity, some approximate relative measure of the average size of the solid particles would be obtained; th t clay soils would show large and sandy soils small shrinkages. Subsequent investigation by Tempany [20] appeare l to indicate that the contraction on drying exhibited by any particular soil, depended directly on its content of colloidal clay, and that a simple means was thus provided of calculating the proximate

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content of colloidal clay. From this view-point it seems legitimate to infer that a high percentage of colloidal clay is directly inimical to the successful cultivation of cacao. Such an interpretation appears superficially to be in good accord with the heavy precipitation in Dominica, and the somewhat exacting water requirements of cacao, for a highly colloidal impermeable soil would evidently remain water-logged throughout periods of heavy rainfall, and would therefore be not only physiologically dry* as a result of inadequate ventilation, but might be distinctly toxic, owing to the presence of organic acids ‡ and the reducing potential capacity of the soil solution.

Inspection of Table I will show the nature of the relation established by Sir Francis Watts between the percentage linear shrinkage of the soil on air drying, and the condition of cacao trees growing in two valleys in Dominica. Shrinkage determinations were carried out both on the surface and the subsoils of several cacao fields. A report was then obtained from the manager as to the condition of the cacao growing on the fields which supplied the samples. It will be noted that where the shrinkage of the surface soil was greater than 10 per cent., the cacao was reported to be in poor condition; sample F was, however, exceptional in that respect. Numerical statements as to the condition of the trees were apparently not available. The correlation was nevertheless considered sufficently striking to render it desirable that further information as to the mechanism of soil shrinkage should be obtained. It should be emphasized that the limits of soil shrinkage above which cacao failed to thrive in these two valleys in Dominica might be sensibly different under another complex of aerial subterranean conditions. The presence of shade trees, for instance, might considerably modify the relationship. This aspect of the subject can evidently be more readily comprehended after consideration of the mechanism of soil shrinkage. Attention should be drawn, however, to the differences in amount of shrinkage exhibited by the surface and the subsoil. A marked tendency will be noted (Table I), particularly where the condition of the cacao was good, for the latter to exceed the former.

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* The first effect of oxygen deprivation is an interference with the absorption of water by roots : cf. Livingston and Free [15] ; see also Howard [12] and Bergman [4].

‡ Salisbury [18] has recently pointed out, however, that even completely water-logged soils need not necessarily become more acid, though other attendant evils assert themselves, and cites Gillespie [10] who found that soils treated with excess of water may become less acid, though exhibiting an increased reducing capacity.

TABLE I.

Sample.	Shrinkage per cent.	Condition of cacao.
A. Surface soil	8	Cacao growing well.
Subsoil	12	
B. Surface soil	13	Cacao failing.
Subsoil	17	
C. Surface soil	12	Cacao very poor.
Subsoil	11	
D. Surface soil	9	Cacao doing well.
Subsoil	12	
E. Surface soil	10	Cacao growing well.
Subsoil	15	
F. Surface soil	13	Cacao fair.
Subsoil	17	
G. Surface soil	13	Cacao died.
Subsoil	11	
H. Surface soil	14	Cacao died.
Subsoil	17	
I. Surface soil	8	Good.
Subsoil	8	
J. Surface soil	12	Poor.
Subsoil	10	
K. Surface soil	10	Good.
Subsoil	10	
L. Surface soil	10	Good.
Subsoil	10	
M. Surface soil	10	Fair.
Subsoil	13	

Experimental.

With a view to ascertaining whether the failure of cacao to thrive on soils with relatively high shrinkages (cf. Table I) is to be ascribed to an intolerance of cacao to highly colloidal soils, or whether this interpretation of the results of soil shrinkage measurements requires modification, determinations were made of the soil moisture residues at permanent wilting (the wilting coefficient of Briggs and Shantz [5]), the percentages of moisture at the point of maximum plasticity, and the percentage linear shrinkage on air drying of a number of soils *.

It was considered that the problem could be most readily approached by comparing the percentage linear shrinkage of a number of soils with the estimations of their colloidality. Methods of ascertaining the degree of dispersion of the soil particles, (of Beaumont [3],) it is generally admitted, are lacking in any high measure of precision. The soil moisture residue at permanent wilting has been shown by Briggs and Shantz [5] to be highly correlated both with the hygroscopic coefficient and the moisture equivalent, both of which are closely related to the degree of dispersion and the interior surface of the soil. It has accordingly been employed as one means of forming an approximate estimate of the colloidality of the soil. The wax-seal method of Briggs and Shantz [5], using maize plants (*Zea mays*) as biological indicators of soil moisture conditions was employed in these determinations. Particular precautions were taken to maintain the rates of transpiration low (cf Caldwell [6]). Direct sunlight was excluded, and air movement was reduced by canvas screens; the humidity of the aerial environment was increased during the forenoon by moistening the screens. Five cultures, each containing two plants, have been used for each determination.

The second method adopted in order to ascertain the colloidal content of the soil, was to determine the percentage of water imbibed by the soil at the point of maximum plasticity. The soil's hydration capacity is considered to be practically a function of the interior surface, and has accordingly been held to be an approximate index of the colloidal content. In order to bring the soil into this state, water is slowly added to the soil, which throughout is vigorously kneaded with the hands. As soon as it commences to adhere to the skin or to unglazed paper, the further addition of water is stopped; the soil is then allowed to dry, and throughout this period is kneaded. The moment at which it no longer adheres to the skin or to unglazed paper marks the point of maximum plasticity; at this stage the soil gels commence to pass into the sol state. Rohland [17] has argued that the moisture content of plastic clay is a measure of the colloids, because as soon as sufficient water is present to

*The mechanical effect of shrinkage on the root system has not been entertained as a possible explanation, owing to the nature and distribution of the rainfall in Dominica.

dissolve the coagulable colloids, a saturation point is reached and no more water can be added without the clay losing its stiffness.*

The method of measuring the linear shrinkage of the soil on air drying was similar to that introduced by Watts [22], and subsequently employed by Tempany [19]. The soil, on being brought to the point of maximum plasticity was moulded into the form of bricks, 3 by 1 by 1 inches in size, into which two fine pins were inserted at a distance of as nearly as possible 50 millimetres apart, the actual distance being found by careful measurement. The bricks were then set aside in a cool shady place to dry ; they were turned occasionally to promote even drying and to avoid warping ; as the process of drying proceeded, the distance between the pins was measured from time to time until the shrinkage ceased ; the results are stated in terms per cent. of the original distance between the pins. Five replicates were run for each determination.

The moisture residues at permanent wilting, the moisture contained by the soil at the point of maximum plasticity,† and the percentage linear shrinkages were measured in the following seven soils, four of which were obtained from Barbados, while three were artificially prepared :—

A. Yellow-red clay loam.
B. Rust red clay loam.
C. Black clay.
D. Grey clay.
E. 2 parts (volumetric) of black clay to 1 part sand.
F. 1 part „ „ „ 1 „ „
G. 1 „ „ „ „ 2 parts „

The natural soils A,B,C,D were air-dried, and the coarser particles removed by passing through a sieve of 2mm. mesh The preparation of the artificial soils E,F,G, was necessitated by the fact that all the Barbados' soils examined were of very nearly similar ' physiological heaviness,' as indicated by their moisture residues at permanent wilting, and by the fact that the importation of soils from the neighbouring islands was considered inadvisable.

The results of these determinations, together with the ratios between the percentages of moisture at the point of maximum plasticity, and the percentage linear shrinkages are presented in Table II.

Inspection of the table shows that a good general correlation exists between the soil moisture residues at permanent wilting and the percentage of moisture at the point of maximum plasticity. It is patent, on the other hand, that no such relationship exists between the latter and the linear shrinkages. It is manifest that if the linear shrinkage is even approximately proportional to the colloidal content of the soil,

*The soils were left for some days in a moist condition to ensure completion of imbibition.

†Expressed as percentages on the oven-dry basis.

it should be highly correlated both with the moisture residue at permanent wilting, and the percentage of water at the point of maximum plasticity. Auchinleck[1] has drawn attention to the lack of proportionality between shrinkage and the water content of the plastic brick. If they both depend, he says, on the percentage of clay present, as is assumed, the proportionality should be very exact. In a gel, the total contraction in volume on air-drying is doubtless very nearly proportional to its hydration capacity.*

In the soil, the conditions are naturally quite different. The modern view is that the soil is a system of mineral particles of all sizes, which are covered with a colloidal film, and that this film is relatively thicker the smaller the particles (cf. Beaumont, Keen [19]).

In the great masses of agricultural soils the particles are aggregated to form compound particles. Comber [7] conceives these aggregates as having large nuclei surrounded by particles which become smaller and smaller from the centre of the aggregate outwards, the clay ultimately imposing its 'emulsoid' nature on the whole aggregate, and on the whole soil in normal cases. The crumb, which is generally regarded as meaning a relatively large loose aggregate (cf. Hilgard [3]), is formed through the combination of these colloidal aggregates, though doubtless no sharp line can be drawn between the two. The crumb, of course, may be largely resolved into its component compound particles when the soil is kneaded in bringing it to the condition of maximum plasticity. The more firmly cemented compound particles, on the other hand, are disintegrated (peptisid deflocculated) with greater difficulty (e.g. through the agency of electrolytes, heating, the passage of an electric current). It is improbable that they are disintegrated to any marked degree in kneading the soil prior to the determination of the amount of shrinkage. Moreover, if the surface tension at the interphase between the particles and the soil solution is the factor which determines the agglomeration of the particles (cf. Frees, Sharp[19]) it is possible that any disintegration which may occur in the process of kneading is merely temporary, and that as the plastic soil dries, reflocculation takes place. The distintegration into well defined aggregates may be observed, for instance, on immersing the air-dried brick in a relatively large volume of water,

On the assumption that the compound particles are not destroyed, at least permanently, in kneading the soil preparatory to shrinkage determinations, it is possible to frame a tentative hypothesis to explain the relatively small shrinkages exhibited by the two most colloidal soils A and B (Table II). At the point of maximum plasticity, the soil gels are regarded as saturated with water and ramifying through the brick. Water must also be present to some extent in the interstices between the particles,

*As a gel imbibes water it swells, but the volume gel + water is less than the original volume of the two components. Swelling, therefore, is accompanied by compression of the water, so that the increase in volume is not apparently a linear function of the water imbibed. The converse should also hold, viz, that shrinkage on drying is not directly proportional to the hydration capacity.

TABLE II.

Soil.	A.	B.	C.	D.	E.	F.	G.
(a) Soil moisture Residue at Permanent Wilting.	33·2 ± 0·33	31·3 ± 0·14	27·1 ± 1·07	25·0 ± 0·33	17·3 ± 0·45	16·4 ± 0·76	13·6 ± 0·73
(b) Moisture Content at Point of Maximum Plasticity.	48·2 ± 0·99	45·5 ± 0·14	43·9*	39·8 ± 0·10	35·4 ± 0·25	30·8 ± 0·14	24·0 ± 0·33
(c) Percentage Linear Shrinkage.	8·8 ± 0·16	8·2 ± 0·08	15·2 ± 0·21	11·8 ± 0·11	10·6 ± 0·22	7·6 ± 0·10	3·7 ± 0·18
Ratio $\frac{b}{c}$	5·48	5·55	3·33	3·37	3·34	4·05	6·49

* Only 3 obsrvations.

both aggregated and not aggregated. The hydration capacity as determined by the percentage of water at the point of maximum plasticity cannot, therefore, be exactly proportional to the interior surface. Three fairly well-defined stages may be distinguished in the progressive loss of moisture which accompanies shrinkage.

In the first the movement of water from the interior of the brick occurs as rapidly as it evaporates from the surface, the contraction in volume being proportional to the amount of water loss.

The second stage commences when the internal friction, due to the approach of the soil particles, both aggregated and not aggregated, becomes sufficiently pronounced to exert a retarding effect on the rate of contraction. Throughout this stage evaporation continues from the surface of the brick alone, for the whole is still completely permeated with water. The water of course passes into a state of tension as a result, on the one hand, of the steady pull due to evaporation, and, on the other hand, to the increasing resistance to further shrinkage opposed by the approach of the soil particles. Throughout this stage there is a gradual diminution in the rate of shrinkage in relation to the corresponding rate of water loss (cf. Tempany [20]). The second stage terminates when the tension becomes sufficiently pronounced to cause a rupture in the continuity of the water permeating the brick; air bubbles appear in the interstices, and consequently the tension ceases.

In the third stage the continuity of the water no longer exists, and, therefore, the shrinkage of the brick as a whole ceases. The evaporation of water continues, however, into the soil interstices.

It is patent that, in soils in which there occurs a marked aggregation of particles, the resistance to shrinkage will be relatively greater than where the colloids exist in a more diffused state.

From this it follows that, the rate of development of the critical tension at which the rupture of the stressed water of the brick occurs, will depend for a given colloid content, rate of evaporation, temperature, and tensile strength of soil solution, upon the degree of aggregation of the soil particles.

The portion of the total moisture contained in the plastic brick which is lost at the moment shrinkage ceases, must therefore be greater the more diffused the condition of the colloids. And since the amount of linear shrinkage is assumed to be proportional to the water lost through evaporation before contraction of the brick ceases*, it must follow that the shrinkage is greater the more diffused the colloids.

Moreover, where the aggregation of particles is considerable, and where the size of the interstices is accordingly large, the absence of resistance to the growth of air bubbles, when the water in the brick passes into a state of tension, will permit a rupture in the continuity of the water, and a consequent cessation of shrinkage, while the tension is still relatively small It can be

*The relationship between linear contraction and water loss is not of course strictly linear in character (cf. Tempany [20]).

readily realized, therefore, that shrinkage should be greater the more diffused the condition of the colloids. From these considerations it would appear that the diffusion of the colloids should be less in soils A and B than in either C or D (Table II); and though the former pair are more highly colloidal than the latter, they should at the same time be more permeable to water and air. It will be remembered that the soils A and B were described as a yellow-red and rust-red loam, respectively, their colour being due presumably to the presence of colloidal ferric oxide. This in itself is an index to good drainage conditions (cf. Hilgard [13]), for ferric oxide cannot long exist in soils under poor drainage conditions, owing to the reducing capacity of the soil solutions.

The permeabilities of the four natural soils were compared, however, by placing equal volumes of the air-dried soils in Buchner filters (2 cm. columns of soil), and noting the relative rates of water penetration by observing the time required for the percolation of a definite volume of water (15 c.c.) under a uniform head of water. The results are shown in Table III.

TABLE III.

Soil.	A.	B.	C.	D.
Time in seconds for percolation of 15 c.c. H_2O.	75	90	165	220

The method admittedly leaves much to be desired. Nevertheless, the differences are considered to be sufficiently pronounced to warrant the conclusions that the more colloidal soils, A and B, were distinctly more permeable to water than either C or D.

CONCLUSIONS.

It is concluded as a result of the experiments recorded in the preceding section of this paper, that the percentage linear shrinkages exhibited by a soil on air drying is not determined solely by the colloidality of the soil. The amount of shrinkage is conceived to be mainly controlled by two antagonistic factors: on the one hand, the degree of dispersion of the soil particles which determines the soil moisture content at the point of maximum plasticity, and on the other, the degree of aggregation of particles into compound grains, which decides the proportion of this moisture which is evaporated when shrinkage ceases. The greater the colloidality and the less the aggregation, the greater should be the contraction in volume on drying. Thus, for any two soils of similar imbibitional capacity (colloid content), the shrinkage is held to be roughly proportional to the flocculation of the colloids, and therefore to the soils' premeability to water.

From this point of view, the failure of cacao growing on soils exhibiting a linear shrinkage of more than 10 per cent. (Table I) is to be ascribed to the conditions liable to attend the diffused

condition of the colloids in such soils; among these conditions may be mentioned impermeability to water, insufficient oxygen for the roots and aerobic soil organisms, resistance to root penetration, and toxicity due to organic acids and the reducing capacity of the soil + water complex. Moreover, the tendency of the surface soil to exhibit smaller shrinkages than the subsoils (cf. Table I) may be explained on the assumption that the aggregation of colloids is greater in the upper regions of the soil.

Measurements of soil shrinkage alone, it is evident, must be very misleading when employed to indicate either the degree of dispersion, or the state of aggregation of the soil particles. It is possible to conceive, for instance, that two soils may exhibit similar shrinkages, but may vary widely both in their colloidality and their permeability to water. Consider two such soils, each with a linear shrinkage of 10 per cent., the one containing 40 per cent. and the other 30 per cent. of water at the point of maximum plasticity. The latter, it will be patent, though the less colloidal, may still be the more impermeable of the two, owing to the diffused condition of its colloids. A statement of the ratios between the water content at the point of maximum plasticity and the percentage shrinkage may be found, however, on further investigation, to be of considerable value as a means of comparing the degree of aggregation of particles in highly colloidal soils. Consideration of these ratios* in the case of the four soils A, B, C, and D, is particularly instructive in this connexion. The first two, it will be remembered (Table II), though more colloidal than either C or D, have been shown to be distinctly more permeable to water.

The need † of a method of readily ascertaining the aggregation of soil particles is very great; for as Russell [16] says, 'the significant units in the soil that determine its intrinsic properties are the compound particles made up of the ultimate mineral particles.' In regions where periods of torrential rain alternate with spells of drought, the existence of adequate aeration during the former, and of physiologically available water during the latter, are the prime conditions determining whether a particular soil is suitable, or the reverse, for the growth of any single kind of plant. To meet these requirements, the soil should possess as high a water-retaining capacity as is compatible with proper drainage and ventilation. The higher its colloidality and the greater the aggregation of its particles into compound grains, the more nearly it fulfils these conditions.

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* It would be more accurate to express this as the ratio of

$$\frac{\text{No. of c.c. of water in}}{\text{No. of c.c. of shrinkage of}}$$

a brick of 100 c.c. at the point of maximum plasticity'

†Keen [14] cites some work of Mitscherlich, who has approached this problem by attempting to ascertain the total interior surface by measuring the soil's hygroscopicity over 10 per cent. sulphuric acid in a vacuum desiccator, and the total outer surface of the particles and aggregates by replacing the acid by a liquid of high molecular weight, which is supposed to condense only on the outer surface of the compound particles. For ecological purposes, the use of the hygroscopic coefficient as an index to the total surface, and the determination of the diffusion of colloids by sedimentation (cf. Hoagland and Martin [11]) would probably afford a more reliable index to soil texture than any method at present in general use.

A diffused condition of the ultimate particles brings inits train a compact, impermeable, badly aerated soil ; such soils are unfortunately very common at present in the West Indies. Earle [9], for instance, has recently pointed out that root diseases of the sugar-cane, in common with other diseases due to facultative parasites, are as a rule best controlled by improved cultural methods, the employment of properly balanced fertilizers, attention to drainage, and keeping the soil *porus* and *open*. William's work [23] on the Froghopper blight of sugar-cane in Trinidad is of considerable interest in this connexion. The blight was found to be worse on heavy sour soils than on light, well aerated, well limed soils. 'The acidity,' he points out', 'is probably more an indication of the *physical condition* that has brought it about: all the acid soils were heavier and more impervious than the alkaline or neutral undamaged soils.' The attacks of Thrips on Cacao are apparently in a large measure to be traced to a similar source (cf. Ballou [2] ; see, however, Urich[21]).

The diffused condition of colloids and the resulting diminution in permeability are apparently associated with the removal of particular agglomerating ions from the soil. Sharp[19], for instance, has shown that a soil may be made considerably more impermeable by the addition of certain sodium salts and subsequent leaching of the soil ; calcium and magnesium appear in the percolate in considerable quantities, the sodium being retained by the soil. The diffusion of colloids is regarded by Sharp as mainly due to the formation of new silicates rather than to the disintegration of the colloidal aggregates. Hoagland and Martin [11] have also recently recorded some work in which it is shown that a very good general correlation exists between the concentration of electrolytes in the soil solution and the diffusion of soil colloids, and that both undergo very marked variations coincidently with seasonal changes and crop growth. That the removal of solutes from the soil solution by the plant in itself results in a diffusion of colloids, is a conception of paramount importance. It cannot be too strongly urged that the plant and its whole environment, both aerial and subterranean, constitute a single system, the component parts of which continually act and react one on the other.

Summary.

(1) Attention is drawn to a correlation established by Sir Francis Watts between the condition of the cacao grown in certain valleys of Dominica and the percentage linear shrinkage of the soil on air drying ; the cacao failing to thrive where the shrinkage exceeded 10 per cent.

(2) An attempt to elucidate the significance of this relationship was made by comparing the percentage shrinkage of a number of soils with their moisture residues at permanent wilting (the wilting coefficient of Briggs and Shantz), and the percentage of moisture in the soil at the point of maximum plasticity.

(3) It was concluded that the amount of shrinkage exhibited by any soil on air drying is not determined solely by its

colloidality or degree of dispersion, but is dependent also on the degree of aggregation of the particles into compound grains, the greater the dispersion and the less the aggregation, the greater the shrinkage for a given temperature, rate of evaporation, etc.

(4) The poor condition of the cacao, under the particular complex of environmental condition of these valleys, when rooted in soils whose linear shrinkage exceeded 10 per cent., has been provisionally ascribed, therefore, to the degree of diffusion of colloids in such soils, and not merely to their colloidal content. Diffusion of soil colloids, it is emphasized, renders the soil impermeable to water and consequently poorly aerated, especially under conditions of prolonged and heavy rainfall.

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THE PHYSIOLOGICAL HUMIDITY OF THE SOIL AND ITS DIRECT DETERMINATION.*

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Statement of the Problem.

This investigation was undertaken with a view to developing a simple method for the direct determination of the soil's humidity in as far as this is directly related to the growth and maintenance of the life of the plant. The elaboration of such a method is prerequisite to the investigation of a large number of problems of pressing economic importance in the tropics. For instance—

(i) the effects of different forms of mulching, cultivation and manuring on the conservation of soil moisture;

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(ii) the premature shedding of cotton bolls and citrus fruits;

(iii) the relation between the aridity of the environment as a whole (aerial and subterranean), and the characters of the lint of cotton;

(iv) the susceptibility of the plant to insect and fungous attacks under varying conditions of environmental aridity.

Introduction.

It is almost universally recognized that a bald statement of the total percentage of moisture in a soil conveys no information as to the soil's ability to supply moisture to the roots of plants. Sachs 11 was apparently the first to recognize that considerable variations in moisture content exist among different types of soils at the onset of wilting. His investigations in this field were confined to tobacco plants, which were grown in three different types of soils—a vegetable mould, a loam, and a quartz sand. It was found that wilting occurred while the soils contanied 12·3, 8·0, and 1·5 per cent. of water, respectively. Subsequent investigation (Gain 11, Hedgcock 2, Clements 7) on the moisture residue in the soil corresponding to the onset of wilting of plants, appeared to indicate that some species were able to reduce the moisture content of the soil to a much lower level than others, and consequently, that the moisture available for growth was a function not only of the nature of the soil and its moisture content, but also of the species of plant. This opinion, it would appear, is still widely prevalent among many practical agronomists, and has sometimes been considered an important factor in determining the degree of drought-resistance exhibited by different species of plants. Briggs and Shantz 5, however, who have published comparatively recently, the results of an extensive series of observations, in which many different types of soils were employed, and more than a hundred different kinds of plants, have come to conclusions which stand in strong contrast to those of earlier workers in this field. By taking many precautions which had not been previously observed, they were able to demonstrate that the variations exhibited by different plants in their ability to reduce the soil moisture before the onset of permanent wilting was much less than had heretofore been supposed, and that the differences between crop plants in this respect was so slight as to be without practical significance in the selection of crops for semi-arid regions The slight differences which they did observe in the soil moisture residues, at the time of permanent wilting of different species of plants, were largely due, they considered, not to the ability of one variety to exert a greater pull than another on the soil water, but to a more perfect root distribution. The moisture content of the soil corresponding to the permanent wilting of the plant, expressed as a percentage of the dry weight, was designated the wilting coefficient of the soil. By permanent wilting is implied, that stage of progressive wilting from which the leaves fail to recover their turgidity within a period of twenty-four hours, when the plants are exposed to a parctically water-saturated atmosphere in the dark. It was concluded that the

soil moisture residue at the time of permanent wilting was not influenced to any appreciable extent by the evaporation conditions of the air, and that a considerable change in light intensity was without any marked effect. Caldwell, however, has demonstrated that their conclusions in this respect must be radically modified, for the soil moisture residue at the onset of permanent wilting has been shown to vary in a regular and predictable manner with the evaporating power of the air. It is evident, as a result of Caldwell's investigations, that it is only when the plant is allowed to wilt in a shaded moist chamber, that the wilting coefficient of Briggs and Shantz assumes the aspect of a soil constant. The physiological classification of the soil's moisture, which results from the studies of Briggs and Shantz, has been summarized by Alway, as follows :—

1. *Water available for growth.*—The difference between the total water content and the wilting coefficient.

2. *Portion of the available water not available for growth, but available for the maintenance of life.*—The difference between the wilting coefficient and the moisture of the soil in equilibrium with the air.

3. *Non-available water*—The moisture content of the soil when in equilibrium with the air, or, in other words, the water content of the air-dry soil. No distinction, however, as Alway points out, was drawn between the physiological importance of the portion of the water between the wilting coefficient and the hygroscopic coefficient*, and that of the portion between the hygroscopic coefficient and the air-dry state. They did, however, make a comparison between the soil moisture content at the wilting point and at the death point as criteria for comparing plants in their relation to soil moisture. The average error in determining the wilting coefficient was found to be considerably less than that accompanying the determination of the moisture content corresponding to the death point. Moreover, the wilting coefficient was found to be practically independent of the kind of plant used as an indicator, whereas the death point varied with the plant used. Alway [1], too, in the course of his investigations on the relation of the non available water of the soil to the hygroscopic coefficient, has observed that some desert legumes remained alive after the water content had fallen slightly, but distinctly, below the hygroscopic coefficient; while wheat, milo, beans and maize plants showed but little difference in their ability to exhaust the soil moisture before the death of the plants. Alway has therefore felt justified in employing the hygroscopic coefficient as a datum for comparing the amount of physiologically available water in different soils. The percentage of water in excess of the hygroscopic coefficient has been designated 'free water.' The use of the hygroscopic coefficient as a datum for estimating the reservoir of available water in the soil, possesses the advantage that it does not overlook the importance,

* The hygroscopic coefficient expresses the percentage of moisture contained in a soil, which in an air-dry condition is brought into a saturated atmosphere, kept at constant temperature, and allowed to remain until in approximate equilibrium with this atmosphere. It provides apparently a simple means of forming an approximate estimate of the degree of dispersion or interior surface of the soil.

for the maintenance of life, of the portion of the soil moisture between the wilting coefficient and the hygroscopic coefficient; it can, in addition, be readily determined with comparative facility. On the other hand, it is apparently merely an index to the interior surface of the soil; and though it is unquestionably often very markedly correlated with the soil moisture residue at permanent wilting, it does not appear to rest on any very definite physiological basis; and moreover, is not directly related to the rate of water migration through the soil, a factor of evident moment in determining the rate at which water may be supplied to plant roots.

It will be recognized that a statement of the growth-water (the difference between the total percentage of moisture in a soil and the wilting coefficient of Briggs and Shantz), or of the amount of free water (the difference between the total percentage of moisture in a soil and the hygroscopic coefficient), though valuable for purposes of comparing the reservoir of physiologically available moisture in soils, affords no criterion to the intensity of the forces with which a soil withholds moisture from a plants' roots (i.e., the back-pull due to the soil). Thus, Alway[1] points out that corn plants may be dying in a soil with a hygroscopic coefficient of 15 and containing 3 per cent. of free water, while plants of the same kind in a soil with a hygroscopic coefficient of 0 5, may be very vigorous with 1 per cent. of free water. Such a condition, one persumes, is to be explained on the assumption that the forces with which the former soil retains its moisture (with 3 per cent. of '(free-water)' are greater than those of the latter (with 1 per cent. of 'free-water'); or to state the case in another way, that the hygroscopic and capillary forces of the former soil with 18 per cent. of water are less nearly satisfied than those of the latter with 1·5 per cent. of moisture This aspect of the subject is apparently somewhat analogous to the distinction which is drawn between the total acidity and the hydrogen-ion concentration of physiological solutions. A mere statement of the total acidity offers no information as to the intensity of the acidity, which alone is of direct biological significance; similarly a bald statement of the amount of growth —or free-water—is bereft of physiological meaning unless accompanied by a knowledge of the wilting or of the hygroscopic coefficient as the case may be. Alway and McDole[2], [3] have accordingly employed the ratio of the total moisture content to the hygroscopic coefficient as an index to the physiological humidity of the soil. Thus, a ratio of 1·7, for example, might indicate a soil with a hygroscopic coefficient of 10 and a total moisture content of 17 per cent. or it might denote one with a hygroscopic coefficient of 5 containing 8 5 per cent. of moisture. Of a somewhat similar nature is the coefficient of soil humidity proposed by Crump [8], which is defined as the ratio of the total percentage of moisture* to the humus content. It is naturally only of value in peats and soils containing large quantities of organic colloids. It would apparently be equally logical to express the physiological humidity of the soil as the

* The moisture content is determined by measuring the loss of water after thorough air drying at 15°C., and the humus content by the loss in weight when the peat, previously heated at 100°C., is ignited to a dull red heat.

ratio of the total moisture content to the moisture equivalent†, or to any other index to the colloid content or interior surface of the soil. Methods of this nature, which aim at expressing the ratio of the total moisture to the interior surface of the soil are clearly of considerable value, but are not without certain objections. In the first place, they evidently proceed on the assumption that the force with which the soil retains its moisture is a linear function of its moisture content; an assumption which is unjustified in view of Shull's [18] work on surface forces in soils. In the second place, no account is taken of the differences which exist in facility of water transmission among different soils, which is a function not only of the colloidal nature of the soil but of a number of soil properties which cannot yet be readily characterized. Recognizing the difficulties involved in obtaining an expression for comparing the relative moistness of soils by the integration of such static features, Pulling and Livingston [15] have approached the problem from the dynamic point of view, and have elaborated a method of measuring directly the water-supplying power of the soil, somewhat in the same way as the evaporating power of the air is now determined by direct methods, without recourse to the integration of such features as air temperature, moisture and movement. The method consisted in observing the rate at which a solution of known concentration in a thistle-osmometer withdrew water from the soil. The water-attracting forces exerted by the solution were opposed by the surface forces retaining the moisture in the soil and the osmotic pressure of the soil solution. The difficulties involved in maintaining adequate contact between the adsorbing membrane of the osmometer and the soil, rendered the method more suitable for laboratory use than for work in the field. Recently another method has been proposed by Livingston and Koketsu [13] in which advantage is taken of the marked water-attracting forces of dry porous porcelain. Artificial roots of porous porcelain, for which the term soil-points is temporarily employed, are placed in the soil for a definite period, and the weight of water imbibed is employed as an index to the water-supplying power of the soil. With a view to ascertaining whether the assumptions on which the proposed method had been based were legitimate or not, the water-supplying powers of a number of soils of varying texture were determined by the porcelain soil-points at the onset of permanent wilting. At this critical stage, all soils, irrespective of their textures, are to be considered as similar in their ability to supply water to the roots, and should, therefore, if the assumptions on which the method were based were correct, be alike, in their capacity to supply water to the artificial roots employed. For a large range of soils studied the soil-points registered practically the same water-supplying power. It was with a view to testing further this method, possibly simplifying it and introducing a modification of detail, so rendering it available for the analysis of ecological and agricultural problems, that the present investigation was undertaken.

† The moisture equivalent of a soil is the percentage of water left in the soil after centrifuging for a certain time under a force of 1,000 gravities, a force about equal to one atmosphere. Sharp and Waynick (*Soil Science*, 4,6,463-69, 1917.) have employed it as an index to the interior surfaces of soils.

Method.

The principle of the method adopted was similar to that of Livingston and Koketsu In place, however, of porous porcelain soil-points, hard-leaded writing pencils * were employed a the suggestion of Dr. Livingston. The imbibitional forces of the wood have been found to be satisfactory for this purpose. A very nearly constant absorbing area was readily obtainable by using an ordinary mechanical pencil sharpener; the rest of the surface except the unsharpened end, which was sealed with paraffin wax, remaining water proofed by the varnish of the pencil. A number of these pencil soil-points, after standardization and 'sharpening', were weighed and inserted in the soil for a definite period, the hard lead of the pencil assisting the penetration of the conical absorbing surface. As the absorbing surface came to rest, contact between it and the soil was attained in a manner somewhat similar to that between a growing root and the surrounding soil. In both cases the soil immediately about the absorbing surface becomes somewhat compressed. It is evidently of moment that the compression of the soil should approximate as closely as possible to that due to the root †, and that it should not differ from one determination to another. Care was accordingly exercised to insert the soil-points slowly in to the soil. If this precaution is neglected, the rate of water transmission may be appreciably accelerated. At the termination of a definite period, the wooden soil-points are withdrawn, and, after the careful removal of adhering soil by a cloth, reweighed. The gain in weight is taken to be an index to the water supplying power of the soil. A celluloid case to prevent water loss while the soil points are being transported between soil and balance has been found unnecessary with the laboratory conditions under which this work was carried out, but naturally would be essential for field observations.

As soon as contact is established between the soil water and the absorbing surface of the soil-point, a movement of water is initiated. The soil region in immediate contact with the absorbing surface is thereby partially dried, and its attraction for water consequently increased. Meanwhile the active area of the soil-point is correspondingly moistened, and its attraction for water accordingly diminished. The rate of reduction in the water-attracting forces of the soil-point is naturally more rapid the greater the humidity of the soil. By inserting the soil points for only a relatively short period in the soil, this factor has been found to offer no particular difficulty.

The results accruing from the tendency of the soil in the region of the soil-point to become progressively dried are more difficult to gauge. The first effect of this desiccation is clearly to augument the water attracting forces of this region of the soil, and thus occasion a movement of water to replace that absorbed by the soil-point. If, however, for the period of a test, the migration of water through the soil occurs at approximately

* 'Koh-i-noor. 6.H. Made by L, and C. Hardtmuth. Vienna.

† It seems desirable that the angle of the absorbing cone should be small.

the same speed as that at which it is removed by the soil-point, the rate of water movement from the soil into the soil-point remains nearly uniform during this period. Assuming then that the rate of water movement does remain uniform throughout the period occupied by the test, and that the two major factors on which the relative rates of movement from soil to soil-point at different soil moisture contents depend are, firstly, the relative ratios between the water-attracting forces of the soil and the soil-point, respectively; and secondly, the resistance opposed by the soil to water movement, the results attending the use of soil-points whose water-attracting forces are greatly in excess of those of the root may be briefly traced. It will be immaterial what moisture contents are assumed, but for convenience, the percentages of water corresponding to the moisture equivalent and the wilting coefficient of Briggs and Shantz will be considered. At the former the moisture is retained by the soil with a pressure of approximately one atmosphere, and in the latter, according to Shull [18], with a force of about four atmospheres. The ratio between the water-attracting forces of the soil at these two moisture contents and the absorbing surface of the soil point are 4 and 1, respectively, irrespective of the water attracting forces of the soil-point; and, since the soil feature to be measured is purely a relative conception, the magnitude of the water-attracting forces of the soil-point should be immaterial. But by assumption, the relative rates of moisture movement from soil to soil-point at different moisture contents are also controlled by the resistance to water movement opposed by the soil. Now this resistance at relatively low moisture contents, when the soil water exists entirely as water of imbibition, must be extremely large, and, moreover, should increase more rapidly than in a soil of relatively high moisture content, for a given augmentation in the water-attracting forces of the soil-point may be of considerable importance, and should approximate as closely as possible to those of the plant root. If greatly in excess, the water supplying power indicated by the soil-point at high moisture contents, as compared to that at low contents, may be much greater than if a soil-point with water-attracting forces approximating more closely those of the root had been employed. One is here confronted with the difficulty that water-attracting forces of the roots are not only very variable, fluctuating in the course of a single day with the evaporating power of the air, but are also comparatively small; according to Shull, the pressure with which the soil holds its moisture at the onset of permanent wilting is only about four atmospheres. It seems improbable that the water-attracting forces of the root are ever greatly in excess of this.

It will be patent though, that where the water-attracting forces of the soil-point are as small as this, that an inconveniently long period would be required to carry out a test. It was therefore decided that the most satisfactory solution would be to use the soil-points while in moisture equilibrium with the air. The unvarnished ends were accordingly water-proofed with paraffin wax, and the soil-points used as required. After a test had been carried out, the absorbing end was cut away for about a quarter of an inch and then sealed. Before resharpening for

a second test, the parafin wax seal was removed with a knife. In this way it was found that no sensible error was introduced on using the soil points a second or even a third time.

The Time period Required for A Test.

The following experiments were undertaken with a view to ascertaining the most suitable time-period for a test of the water-supplying power under varying soil moisture conditions. A black clay was air dried and passed through a 2 mm. sieve. After thorough mixing, it was moistened by the addition of varying amounts of water and placed in a metal container 30 × 25 × 25 cm. In order to ensure an approximately uniform degree of compression (packing) in the moistened soils, the container was repeatedly tapped on the ground until no further reduction in volume could be observed. In the case of the soils of higher miosture content (above 36·4 per cent., Table I.) it was found impossible to bring them to their final moisture content before insertion in the container without undue adhesion occurring between the soil particles. These soils were accordingly

Table I.

Weight of water (hundredths of a gram) absorbed by two Soil-Points from a Black Clay Soil.

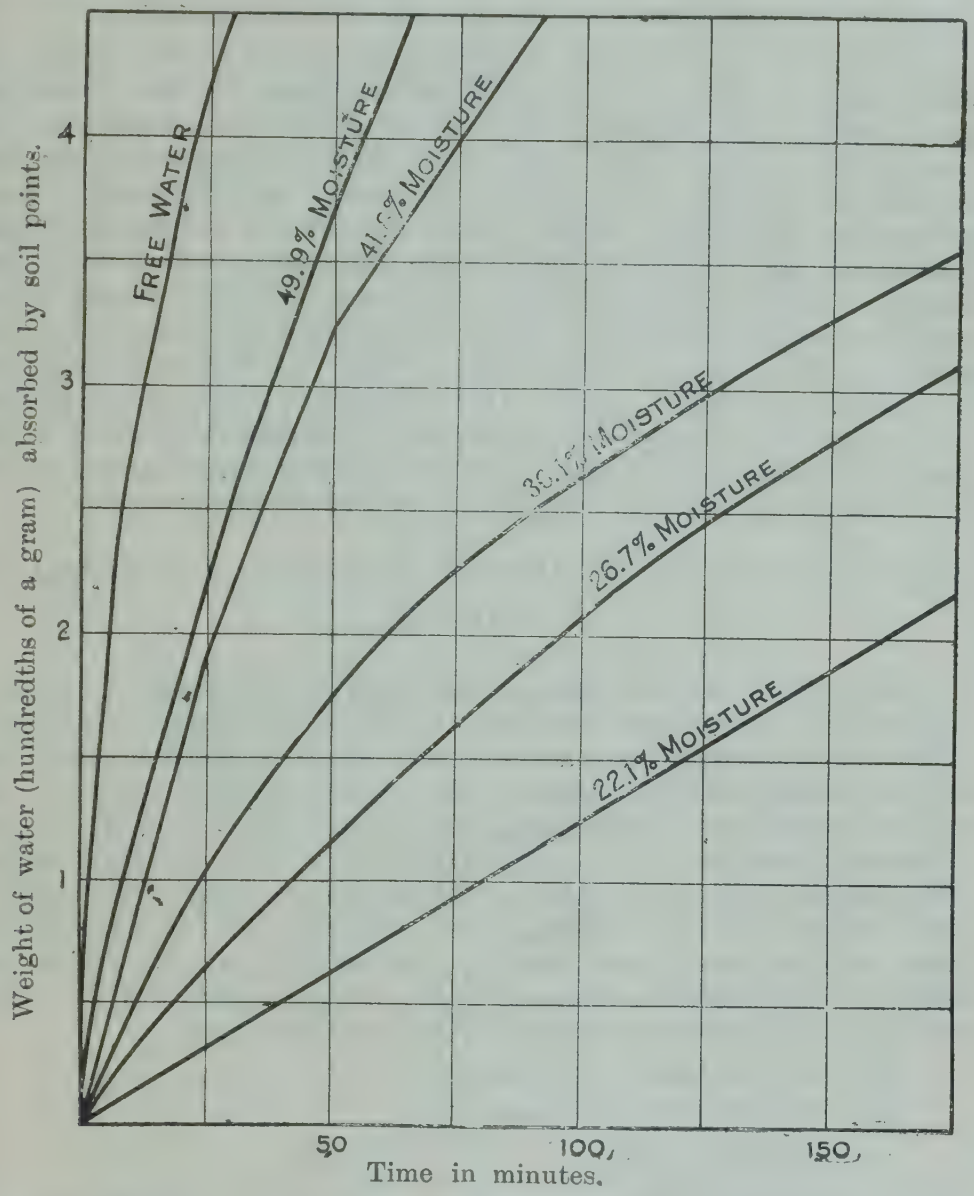
Time in minutes.	Percentage Moisture in Soil (on dry weight basis).					
	22·1	26·7	35·7	36·4	41·8	9·49
50			1·9	2·0	3·2	3·7
75			2·1	2·4	3·9	5·0
100		2·1	2·2	2·9	5·6	6·5
125			2·9	3·0	5·5	6·6
150	1·4					
200		3·3	3·7	3·5	9·3	7·8
300	3·7	4·6				
400	4·5	5·4				
600	5·5					

Table II.

Weight of water (hundredths of a gram) absorbed by two Soil-points from Free Water.

Time in minutes	5	10	15	20	30
Weight of water	1·5	3·0	3·2	4·0	4·4

brought to their full water content after insertion in the container by moistening the surface as uniformly as possible, and leaving for a period of four days to ensure adequate moisture distribution. In order to prevent evaporation, the surface was sealed with paraffined paper. The soil-points were weighed two at a time, and inserted in the soil to a depth of approximately 5 inches. On withdrawal from the soil, adhering particles were carefully removed with a fine cloth, and the gain in weight determined by reweighing.*



In Table I the results of a series of determinations carried out on the soil at six different moisture contents (expressed gravimetrically on the oven dry basis) are presented. Each result represents the mean of two observations, and for each observation two soil points were employed. A result therefore involved the use of four soil-points. The results are expressed

* The gain in weight due to the adhesiveness in the soil was determined by plunging the soil-point into the soil and instantly removing; it was not found to introduce any appreciable error.

as the weight of water in hundredths of a gram imbibed in a definite period. The degree of accuracy obtainable by the use of only four soil-pointsis admittedly small, but is sufficient to permit an estimate to be formed of the most suitable time-period of insertion for a test of the water-supplying power of the soil. For the purposes of reference and comparison, the rate of water absorption by the soil-points from free water are recorded in Table II. The absorbing area was placed just beneath the surface of the water. Each result in this case represents the mean of four observations involving the use of eight soil points.

The results recorded in Tables I and II are reproduced graphically in Fig. 1; but only those fractions of the curves are given which are requisite for an estimate to be formed of the time-period throughout which the rate of water absorption remained uniform. It will be observed that the rate of water movement remained almost constant for a period of thirty minutes at all the soil moisture contents employed in the experiment. At the lower moisture contents a much longer period may be employed, as the rate of absorption remains approximately constant for a considerable period. It will be evident that by making two tests, one of thirty minutes and another of three hours, the water-supplying power can be ascertained over a wide range of moisture contents. Where merely comparative results are wanted, the time-period loses much of its importance.

The Water-Supplying Power of the Soil at Permanent Wilting.

Since the method under investigation purposes to give an index to soil moisture conditions in as far as these influence the plant, it is necessary to adopt some critical physiological state of the plant, which is related to its soil moisture supply, and to determine the water-supplying power of a number of soils of varying texture, while the plants are in this critical condition. Permanent wilting is the most easily recognizable stage in progressive wilting fulfilling this condition, and has accordingly been employed in these studies. Seven different soils were used, four of which were obtained from different parts of the island of Barbados, while three were artificially prepared.

A. A yellow-red clay loam.
B. Rust-red clay loam.
C. A black clay.
D. A grey clay.
E. 2 parts (volumetric) of black clay to 1 part sand.
F. 1 part „ „ „ „ „ 1 „ „
G. 1 „ „ „ „ „ „ 2 parts „

The natural soils A, B, C, D, were air-dried, and the coarser articles removed by passing through a sieve of 2 mm. mesh.

The preparation of the artificial soils was necessitated by the fact that all the Barbados soils examined were of nearly similar physiological heaviness, as indicated by the wilting coefficient

Briggs and Shantz, and the fact that the importation of soils from the neighbouring islands was considered inadvisable The wax seal method of Briggs and Shantz [5], using maize plants (*Zea mays*) as biological indicators of soil moisture conditions, was employed. Particular precautions were exercised to keep the rates of transpiration low. Direct sunlight was excluded, and air movement reduced by canvas screens ; the humidity of the aerial environment was also artificially raised during the forenoon by moistening the screens. The selection of corn as an indicator was possibly unfortunate, owing to genetic heterogeneity and the difficulty of detecting the first stages of permanent wilting. Five cultures, each containing two plants, were employed for each soil. Each culture was placed in an approximately saturated atmosphere for twenty-four hours, as soon as the plants reached the permanent wilting stage, and if recovery occurred the culture was discarded. The water-supplying powers of the soils were then ascertained by means of the pencil soil-points, a period of three hours being used for each test. The percentage of moisture in each culture was next ascertained ; the error introduced into the latter determination through the removal of water by the soil-points was of course quite negligible. The results are presented in Table III. The water-supplying powers of the soils have been recorded as the weight of water, in hundredths of a gram, imbibed in a three-hour period by two soil-points ; fifteen tests were made for each soil, three in each culture. It will be recognized that the soils were alike, in their ability to supply water to the plant's roots as indicated by the loss of turgor and wilting of the plants,* and should, therefore, since the method aspires to measure the physiological humidity of the soil,† register by the soil-points similar values for their water-supplying powers. Reference to Table III shows that the values obtained ranged from 2·40 to 3·23, and that for the natural soils, A, B, C, and D, it ranged from 2·95 to 3·23. It will be patent, therefore, that the values registered by the soil-points are not identical, for the soils exhibited small though statistically significant differences in this respect. The total range, however, for the seven soils is only 0·83, whereas the range of water-supplying power of the soil at the moment of permanent wilting and of free water is approximately 47 (50‡-3). It will thus be seen that the differences in the water-supplying powers exhibited by the seven soils at permanent wilting are negligible in comparison with the total range of water-supplying power liable to be encountered by the roots. The soil moisture residues at permanent wilting it will be noted, varies from 13·6 to 33·2 per cent. Inspection of Table III also shows that, though appreciable variations are exhibited by both soil moisture residues at permanent wilting and water-supplying powers between the cultures of some of the soils, yet the two are only slightly correlated. It will be evident

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* It should be noted that the soil moisture residues at permanent wilting will in general tend to be too low ; this is due the difficulty involved in detecting the *onset* of permanent wilting.

† Only of course in non-toxic, non-saline, and thoroughly aerated soils.

‡ Calculated to a three-hour period. See Table III.

that any lack of uniformity in soil compression (packing) may make the various cultures of a single soil show differences in their moisture residues at permanent wilting On the other hand, as Dr. Livingston, points out (in lit.), 'with the same evaporation conditions, and with the same kind, age, size, etc., of plant, a given phase of wilting should always correspond to a definite water-supplying power of the soil.'

The Water Supplying Power of the Soil at the point of Maximum Plasticity.

It was deemed desirable to ascertain the water-supplying powers of the soils at the time the plants were in some other critical condition depending on their soil water-supply, in addition to that of permanent wilting. Unfortunately there are great difficulties involved in the recognition of any critical stage in the progressive loss of turgor which precedes permanent wilting. This object might have been achieved if it had been possible to bring the soil into any definite moisture condition bearing a constant relation to the wilting coefficient of Briggs and Shantz Inasmuch, however, as the latter can no longer be considered a soil constant, it will be evident that this solution of the problem is out of the question. It was therefore decided to bring the soils into some state, which was a function only of its interior surface. The soil moisture content at the point of maximum plasticity appeared to approximate this condition as closely as any other. According to Rohland[16], the water of imbibition of the soil in this state is a measure of the collodial content of clays; the condition of maximum plasticity apparently marks the point of saturation of the soil gels. In order to bring the soil* into this state, water is gradually added and the soil thoroughly worked. As soon as it commences to adhere to the skin or to unglazed paper the addition of water is stopped; the soil is then allowed to dry, and throughout this period is kneaded by the hands The moment at which it no longer adheres to the skin or to unglazed paper marks the point of maximum plasticity; at this stage the gels, it seems, commence to pass into the soil condition. The soil-points were allowed to remain in the plastic soil for a period of thirty minutes; the results, however, which are shown in Table IV have been calculated to a three hour period (in each case). Five samples of each soil were prepared *independently* and placed in glass tumblers, which were then sealed with paraffined paper. It will be observed that the water of imbibition varied from 24·0 to 48·2; and that the maximum error of the mean of five samples is less than 2 per cent. The water-supplying powers, though agreeing closely in soils B, C, D, and F, show a range of 7·0 between soils A and E. It will also be seen that the water-supplying power of the soil at the time of permanent wilting is only about 21 per cent. of that at maximum plasticity.

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* The soils were left for some days in a moist condition to permit the colloids to imbibe water. (c f. Beaumont, A. B., Memoirs, Cornell University Agricultural Expt. Station, 21, 1919.)

Discussion.

(a) The existence of a critical soil moisture content at which the plant attains its optimum development has received a certain amount of attention in the past. Free[10] has sugg sted that this optimum water content for the plant may correspond to the critical water content at which the soil exhibits its most favourable physical condition. In this connexion the work of Fowler and Lipman[9] on the optimum soil mo sture conditions for young lemon trees on a loam soil is of interest. It was found that the soil m isture percentages within which the young trees made satisfactory growth was, relatively speaking, a wide one; but it is emphasized that i does not follow that the same wide range of moisture percentages would be similarly effective as regards fruit production. It is also of interest to note that the danger to the young trees was found to be greater from too much than from too little moisture in the soil. It must be remembered that the question as to whether there exists an annual optimum water-supplying power of the soil has never been investigated; a mere statement as to a particular range of soil moisture contents outside of which the plant fails to make satisfactory growth contributes very little to its solution unless such factors as soil aeration, physiological balance in soil solution, evaporating power of air, etc., are rigidly under control. In regions where irrigation is not practised, and where a well defined wet season occurs, considerable damage to cultivated plants is liable to result. It will be readily conceived that the augumentation in the water-supplying power of the soil which accompanies torrential rains after a period of comparative drought should normally be followed by a considerable increase in turgor pressure throughout the plant body; in so e cases this is even sufficient to rupture the cell walls.

It has also been observed that a serious shedding of young fruits—e.g., cotton – is liable to occur under these conditions. It is still d ubtful to what extent this is due, either directly or indirectly, to the sudden augmentation in the water-supplying power of the soil, and to what extent to such extraneous factors, as limitation of air supply in the soil or destruction of pollen, and other phenomena which may accompany torrential rains. It will be patent that the rate of increase in the water-supplying power of the soil for a given rate of rainfall should be greater the less colloidal the nature of the soil. The effects accruing from sudden changes in the water-snpplying power of the soil are unquestionably of considerable economic and ecological significance, and could be profitably investigated by means of the soil-point method.

(b) It will be evident that the forces of imbibition of the soil-points, which have been employed in this investigation, operate only against the surface forces with which the soil retains itsmoisture. On the other hand, when an osmometer is used for the determination of the water-supplying power of the soil, work is done not only against the surface forces of the soil but also against the osmotic pressure of the soil solution. Now the water-attracting forces of the plant root, which appear to be numerically equal to that portion of the osmotic concentration

of the cell sap which is in excess of the turgor pressure[14], must also contend with the osmotic pressure of the soil solution. It should follow, therefore, that if permanent wilting were normally due to the development of excessive osmotic pressures in the soil solution, as Bouyoucos and McCool[4] suggest, and if these pressures were to fluctuate considerably from soil solution to soil solution, that the values obtained for the water-supplying power by soil-points, which take no direct account of the osmotic pressure of the soil solution, should show similar fluctuations. It has been found, however, that though significant variations do occur, they are negligible in comparison with the total range of water-supplying power liable to be encountered by the roots of plants. Reference to Table III shows, moreover, that these variations are in general not fortuitous, for a tendency exists for the index of water-supplying power to decline in company with the soil moisture residue at permanent wilting. It is possibly more than a co-incidence that Livingston and Koketsu observed a similar tendency when wheat plants *Triticum sativum* were employed as biological indicators. It is conceivable that this is due to a more perfect root distribution in soils containing a relatively small proportion of colloids.

(c) The ratios between the moisture residues at the time of permanent wilting and the percentages of moisture in the soils at the point of maximum plasticity are shown in Table V. It will be observed that though the degree of correlation is high, yet there is still a considerable range; nearly 40 per cent between the ratios of B and G. It may also be noted that these ratios tend to increase as the value of the soil moisture residues at permanent wilting decrease. This too may be due to a more perfect root distribution in the lighter classes of soil. The nature of the correlation between the soil moisture residues at permanent wilting and the moisture contents at the point of maximum plasticity, appears to indicate, assuming the latter to be proportional to the soil's interior surface, that some factor or factors in addition to the colloidal nature of the soil are responsible for the soil moisture residues at permanent wilting. One presumes that differences in the rate of water transmission through the soil resulting from differences in texture and compression, and the ease of root penetration, must have played a part in determining the soil moisture contents at permanent wilting.

TABLE III.

Water-supplying Power and Soil moisture. Residue at Permanent Wilting.

No. of Culture.			I			II.			III.			IV.			V			Mean.
No. of Observation.			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
Water-supplying Power of Soil at Permanent wilting (hundredths of a gram).	Soil.	A.	2·9	3·1	3·0	3·9	3·3	2·9	3·6	3·4	2·8	3·0	2·5	2·9	3·1	2·7	2·9	3·07±0·063
		B.	3·7	3·0	3·3	3·7	3·0	3·3	2·3	2·8	2·9	2·9	3·1	3·3	2·8	2·6	3·5	3·05±0·071
		C.	2·5	2·1	2·9	3·1	2·6	3·6	2·4	4·1	2·7	2·2	2·7	2·8	3·0	3·6	3·6	2·95±0·096
		D.	3·3	3·0	3·1	3·5	3·7	3·4	2·8	3·1	3·8	3·4	3·2	2·7	3·2	3·2	3·0	3·23±0·056
		E.	2·3	2·1	2·1	2·7	2·4	2·6	2·7	2·4	2·5	2·2	2·2	2·6	2·5	2·1	2·9	2·42±0·044
		F.	3·1	2·6	2·4	2·3	2·3	3·4	2·3	2·8	2·9	3·0	2·6	2·8	2·9	2·3	2·5	2·68±0·059
		G.	2·5	2·6	2·6	2·4	2·2	2·6	2·4	2·9	2·5	2·1	2·4	2·0	2·2	2·9	1·7	2·40±0·053
Soil Moisture Residue at Permanent wilting.	Soil.	A.		25·3			32·4			32·9			33·1			32·5		33·2 ± 0·33
		B.		31·7			31·5			31·1			30·9			31·3		31·3 ± 0·14
		C.		24·5			30·2			24·5			26·9			29·2		27·1 ± 1·07
		D.		23·5			24·6			24·7			25·6			26·4		25·0 ± 0·33
		E.		17·8			15·3			19·2			16·5			17·7		17·3 ± 0·45
		F.		14·4			17·3			15·7			20·4			14·3		16·4 ± 0·76
		G.		11·3			12·9			11·6			15·5			16·8		13·6 ± 0·73

Table IV.

Water-supplying Power and Soil moisture Content at Point of Maximum Plasticity.

No. of Sample.			I.			II.			III.			IV.			V.			Mean.
No. of Observation.			1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	
Water supplying Power of Soil at point of maximum plasticity (hundredths of a gram).	Soil.	A.	14·4	14·4	15·0	27·0	24·6	1·0	10·8	13·2	13·2	29·4	19 8	19·8	1·44	22·2	21·6	18·7 ± 0·99
		B.	12·0	11·4	10·8	19·2	13·8	24·0	11·4	13.2	14·4	10·2	18·6	12·0	10 8	1·0	11·4	13·7 ± 0 68
		C.	12·0	11·4	13·8	10·8	14·4	13·8	13·8	12·6	†	12·0	15·6	15·0	12·0	13·8	14·0	13·2 ± 0·26
		D.	24 6	11·4	13·2	18·6	9·0	10·8	10·8	12·6	10·8	13·2	15·0	15·0	16·8	12·0	13·0	13·7 ± 68·0
		E.	10 8	15·0	10·8	11·4	12·6	8·4	10 8	18·0	10·8	14·4	9·0	†	10·2	15·0	7·2	11·7 ± 45·0
		F.	12·6	14·4	18·0	12·6	14 8	14·4	19·2	12·0	11·4	15·0	17·4	15·0	13·2	12·0	12·6	14·3 ± 0·40
		G.	34·2 *	15·0	18·6	18·0	18·0	15 0	20·4	12·0	18·0	39·0 *	19·2	16·8	27·6	19·8	12·0	1·77 ± 0·74
Soil Moisture content at point of maximum plasticity.	Soil.	A.	50·0			50·9			47·3			49·9			4?·9			48·2 ± 0·99
		B.	47·7			44·3			45·7			43·9			45·9			45·5 ± 0 14
		C.	43·2			43·5			45·1			†			†			43·9
		D.	38·3			39·8			40·3			40·3			40·1			39·8 ± 0·10
		E.	35·3			34·8			35·9			36·5			34·4			35·4 ± 0·.5
		F.	31·4			30·8			30·1			30 8			30·9			30·8 ± 0·14
		G.	23·5			25·9			23·5			23·6			23·3			24·0 ± 0·33

* Not included in mean. † Not determined

TABLE V.

Soil.	A.	B.	C.	D.	E.	F.	G.
(a) Soil moisture Residue at permanent wilting.	33·2	31·3	27·1	25·0	17·3	16·1	13·6
(b) Soil moisture content at point of maximum plasticity.	48·2	45·5	43·9	39·8	35·4	30·8	24·0
Ratio $\frac{b}{a}$	1·45	1·45	1·62	1·59	2·05	1·88	1·76

SUMMARY.

(1) An outline is given of the more important methods which have been employed in the determination of the phsyiological moisture conditions of the soil.

(2) A simple method of measuring directly the water-supplying powers of soils by means of lead writing pencils has been described.

(3) Since soils at the time corresponding to the permanent wilting of plants rooted in them are all similar, as far as their capacity to supply water to the plants is concerned, the values obtained by this method should show a close agreement. This was found to be the case in seven soils of varying texture.

(4) A high degree of correlation was found to exist between the colloid content of the soils, as measured by the water of imbibition at the point of maximum plasticity, and the soil moisture residues at permanent wilting.

In conclusion the writer has pleasure in acknowledging his indebtedness to Dr B. E. Livingston, at whose suggestion the work was undertaken.

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THE PREPARATION OF HIGH GRADE SUGAR-CANE SYRUP.

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Considerable interest attaches to the manufacture of cane syrup, in view of the facts that it is more easily manufactured than sugar, and it commands a price which compares favourably with that of muscovado sugar.

Certain standards are set, however, which must be reached by a marketable article, Tempany (*W. I. B.*, Vol. XIII, p. 324) states: 'The requirements of a good syrup may be stated as follows:—

'I. It should possess a density of not less than 40° Beaumé
'II. It should test not more than 48° and not less than 32° by the polariscope.
'III. It should be free from fermentation and pronounced flavour of acidity.
'IV. It should not crystallize even on prolonged standing.
'V. It should be free from all traces of mineral acid.
'VI. It should be clean, free from suspended impurities, bright, and of a golden colour.'

The manufacture of cane syrup is dealt with at some length in the article referred to above. A somewhat condensed version of this article has appeared in the *Agricultural News* of January 24, 1920.

Since the publication of the articles mentioned, Dr. Zerban, of the Louisiana Sugar Research Institute, has published an account of his experimental work on the defecation of cane juice by certain colloidal agents.* The excellent results which he has obtained by his new process suggested the possibility of its application to the production of high grade cane syrups in the West Indies.

At the same time, in view of the varying nature of the product manufactured in the Leeward Islands, it was considered desirable to ascertain if it would be possible to keep a rather close check on the polarization of the finished product without introducing too complex a system of chemical control to be carried out by any intelligent overseer.

The polarization of a cane syrup depends to some extent on the purity of the juice from which it was made, and on the density of the finished syrup—but to a great extent also on the amount of inversion taking place during its manufacture.

The factors controlling the degree of inversion which takes place during concentration are :—

1. Rate of inversion.
2. Total period of concentration.

The rate of inversion itself depends on several factors—the most important being :—

1. The concentration of the sucrose.
2. The temperature of the reaction mixture.
3. The concentration of the inversion catalyst, i.e. the concentration of naturally occurring acid present.

Factor 2 varies throughout the reaction as the boiling point of the liquid rises with increasing concentration.

The concentration of the catalyst is also a varying factor. Evaporation of the syrup and the consequent diminution in volume tend to increase the concentration of the acid. On the other hand part of the acid formed during the spontaneous souring of cane juice is volatile,* and is lost on evaporation—thus tending to lower the concentration.

It should be noted here, moreover, that it is not the actual amount of ionisable acid present which determines the rate of inversion, but the concentration of hydrogen-ion. This will vary with the acid formed. Hydrogen-ion concentration cannot be measured by titration with alkali, and in the case of a deeply coloured liquid such as cane juice, the simple colorimetric methods for hydrogen-ion estimation become unreliable, and recourse must be made to the hydrogen electrode—too complicated a method to function in a simple manufacturing process.

It has been found, however, that determination of the initial acidity of a juice by titration with N/2 Na OH and phenol phthalein—together with a control of the time factor allows of the production of a syrup polarising within the limits quoted above.

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*Filter-cel : an infusorial earth, and Norit : a vegetable charcoal.
*Watts & Tempany, *W. I. B.*, Vol. VI, p. 387.

Control of the Inversion.

Tempany (*loc. cit.*) recommends the addition of a definite volume of sour juice approximately twenty-four hours old to each batch of fresh juice. The quantity of sour juice required is stated to vary in different districts—from nothing in the northern cane-growing district of St Kitts up to 60–80 gallons per clarifier in the limestone area of Antigua.

The acidity developed under normal conditions in twenty-four hours is stated to vary within relatively narrow limits. On the other hand, the rate of souring in the case of differe t varieties appeared to be subject to variations of some magnitude.

The following figures obtained by us for the acidity o various mixed juices twenty-four h urs old indicate that at times the variation from the mean value may be great enough to affect seriously the degree of inversion taking place.

100 c.c.	equals	12·0 c.c.	$\frac{N}{2}$	acid.
100 c.c.	„	18·5 c.c.	„	„
100 c.c.	„	20·0 c.c.	„	„
100 c.c.	„	22·0 c c.	„	„
100 c.c.	„	28·0 c.c.	„	„
100 c c.	„	29 0 c.c.	„	„

Experiments were made to determine whether, when the time factor was kept constant, any close relationship exi ted between the polarisation of the finished syrup and the initi l acidity of the juice as determined by titration.

Seven batches of syrup were made. The initial acidity of the juices varied from ·043 to ·108 c.c. N/2 acid per c.c. of juice, and was adjusted by mixing fresh and sour juices of known acidity in the desired proportions.

In each case the density of the resulting syrup was 40° B_e and the total time of heating—including defecation,* which was carried out with filter-cel, was approximately two hours.

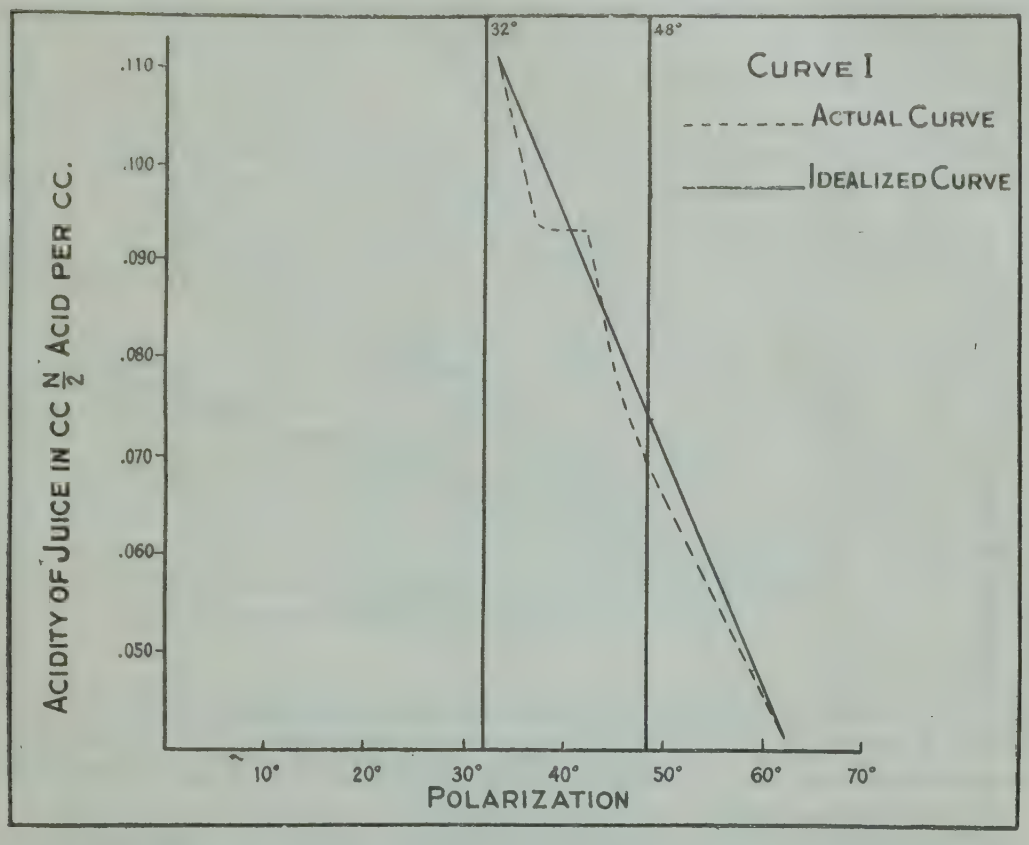
The following results were obtained :—

Experiment.	I.	II.	III.	IV.	V.	VI.	V .
Acidity of juice in c.c. N/2 acid per c.c. juice ...	·043	·054	·066	·081	·093	·093	·108
Polarization of syrup ...	61°	55°	50°	44°	37°	42°	33°

*Defecation with filter-cel exerts but litttle change on the acidity of the juice.

200 c.c. juice of total acidity equivalent to 15·3 c.c. N/2 acid was heated to boiling with 2 gms. filted-cel. The acidity of the filtrate was equivalent to 15 c.c. N/2 acid.

The polarisation values of the syrups are plotted against the initial acidity of the juices (expressed as c.c. N/2 acid per c.c. of juice) in curve I.



As will be seen, the curve approximates to a straight line within the limits of acidity investigated—indicating the close relation existing between the final polarization and the initial acidity of the juice as determined by simple titration.

The time factor was next investigated. A juice whose initial acidity was 1 c.c.=·071 c.c. N/2 acid was converted into syrup of 40° Beaumé in three and a quarter hours The heating during defecation required a quarter of an hour, so that the total time of uninterrupted heating was three hours.

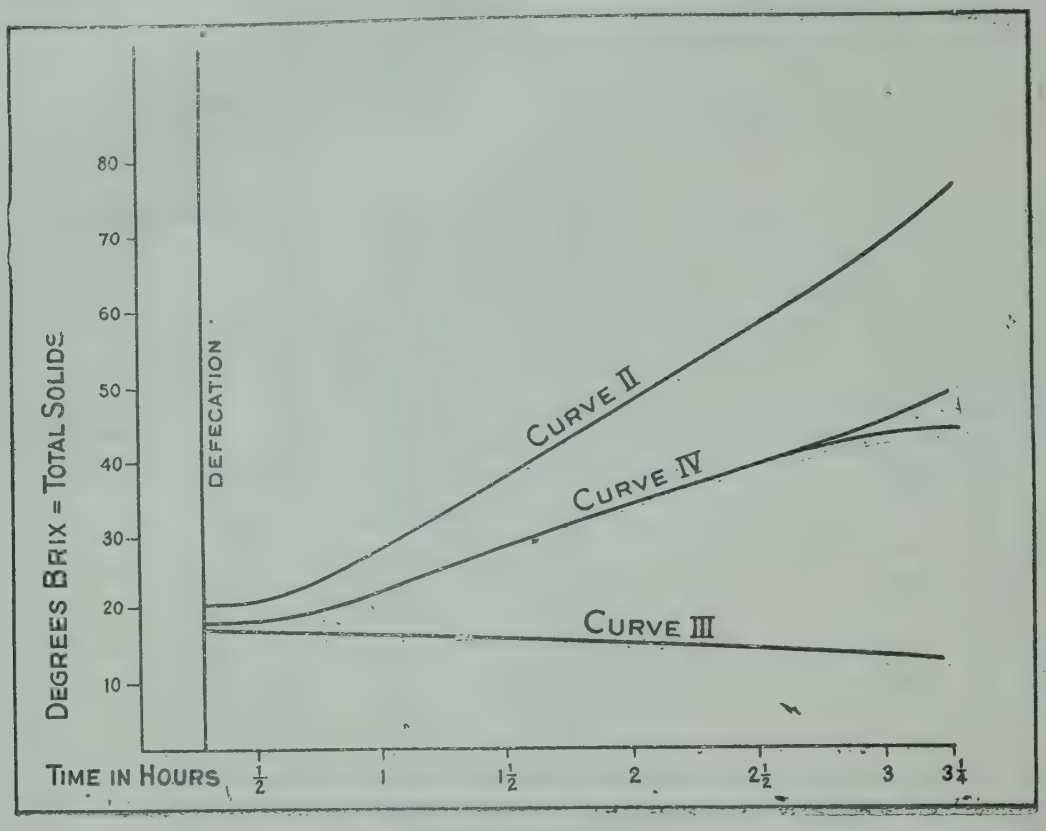
The density (degrees Beaumé) and the polarization of the freshly defecated juice were taken ; and at various intervals further samples were withdrawn for the determination of these values. In each case, besides polarizing the syrup a portion of the sample was diluted to 11° Beaumé (the density of the defecate djuice) and the diluted sample polarized.

The density in degrees Beaumé has been converted into total solids (Brix), and these values and the corresponding polarizations of the diluted and undiluted syrups have been plotted against time in curves II, III, and IV. Curve III is a measure of the inversion taking place during any given period.

The lag in all the curves observed during the first quarter hour period after defecation is due to the fact that the temperature did not reach 100° until the end of this time.

Consideration of the curves indicates that for a syrup concentrated in two hours, an initial acidity of about ·085 c.c. N/2

acid per c.c. is desirable ; while if the time of concentration is three hours, the initial acidity should be about ·075 c.c. N/2 acid per c.c.



In practice it may sometimes happen that the quantity of sour juice on hand is so large that were it all mixed with the available fresh juice, too acid a mixture and consequently too much inversion would result.

It is therefore advisable to manufacture a syrup polarizing somewhat near 48°—the upper limit—so that should at any time the manufacture of a syrup of low polarization be inevitable, an admixture of this low polarizing syrup would not depress the polarization of the mixture below 32°.

The Filter-cel Process.

Defecation. A mixture of fresh and sour juice in the requisite proportions to contain the acid needed to produce the desired degree of inversion is heated to boiling in the course of fifteen to twenty minutes with from ·5 per cent. to 1 per cent. by weight of its volume of filter-cel. The hot liquid is either filtered through felt or flannel bags, or allowed to settle, the sediment only being filtered. In either case the defecated juice is obtained as a clear amber-coloured liquid. ·5 per cent. weight by volume seems to be the lowest limit to the amount of filter-cel which brings about a satisfactory defecation. When the defecated juice is to be filtered, a higher percentage of filter-cel about 1 per cent. gives the most satisfactory results. On the other hand, when sedimentation for a couple of hours is resorted to the volume occupied by the sediment is smaller when the lower percentage of filter-cel is used.

In two sedimentation experiments the following results were obtained:—

A. 1 per cent. filter-cell : Sediment = 18 per cent. total vol. of juice
B. ·5 per cent. „ „ „ = 13 „ „ „ „

Where sedimentation is used, the last portions of the juice which contain the sediment filter readily through flannel, giving a satisfactory filtrate.

Concentration The clear juice is heated over a naked flame until the temperature of the boiling liquid rises to 107-108°C. A sample is then removed for determination of density. If this value is 35° Beaumé in the hot juice, the syrup will have a density of 40° Beaumé in the cold, and concentration is complete.

During the last stage of concentration a gummy froth rises to the surface : this is removed by skimming, leaving a bright golden brown to reddish brown syrup.

In our experiments concentration was carried out in enamelled vessels. In one experiment, however, a number of iron nails—some being rusty—were placed in the boiling juice for the whole period of concentration. No appreciable effect resulted as far as appearance of the syrup is concerned.

Yield.

Yields expressed as c.c. of syrup per 100 c.c. of juice convey little information, as there is a considerable variation in the total solids content and purity of the original juice.

The yield expressed as the percentage of total solids in the juice recovered in the syrup—when accompanied by the purity of the juice—affords a better indication of the loss taking place during the process.

The following results* were obtained in two experiments which were carried out to ascertain the yield :—

Expt.	Weight of total solids in juice.	Purity.	Loss during defecation.	Weight of total solids in syrup of 40° Beaumé	Total loss.	Yield.
I.	348 gms	83%	17 gms.—4·9%	272 gms	76 gms.—21%	78 %
II.	428 „	86%	21 „ =4·9%	372 „	56 „ =13%	87 %

It will be noticed that the loss during defecation proper is small. The further loss of 8 per cent. to 17 per cent. is due to the separation of gummy matter during concentrating : this either sticks to the wall of the concentrating vessel or is removed by skimming. In neither case is it measured with the finished syrup.

Cost of Process.

The highest percentage of filter-cel used is 1 per cent. weight by volume, that is to say ·1 gm. per 10 c.c. which is about equivalent to 1 lb. per 10 gallons.

*Applicable only under laboratory conditions.

In the experiment in which the yield reckoned on the total solids was 87 per cent. 345 c.c. of syrup were obtained from 2,000 c.c. of juice. That is, 345 gallons of syrup would be obtained from 2,000 gallons of juice. For this quantity of juice, 200lbs. filter-cel would be used. This is equivalent to ·58 lb. per gallon of syrup.

Filter cel bought in car load lots directly from the factory costs $1\frac{3}{4}$c. per lb. If we allow $2\frac{1}{4}$c. for exchange, freight and duty, it would costs 4c. landed in the British West Indies—whence the cost per gallon of syrup would be 2·32c.

To calculate the total cost of production, the individual manufacturer must add the cost of fuel and labour, barrels, overhead charges, etc.

It is probable that the filter-cel used could be revivified by ignition at a temperature high enough to destroy the adsorbed organic matter.

The Norit Process.

We have made a few experiments using norit in conjunction with filter cel. The syrup produced was of a fine honey colour, but the difficulty of filtering from the norit prevented a full investigation of the process.

Since the conclusion of the work recorded above, reference has been made in *The Journal of Industrial and Engineering Chemistry*, June 1921, 'The manufacture of Citric Acid from Lemons,' to the use of carbonized filter-cel as a filtering agent. This product is obtained by heating to a bright red heat in closed retorts, the press cake obtained on filtering raw lemon juice treated with filter-cel. It is claimed that the carbonized filter-cel has a decolourising value, and is a much better aid to filtering that fresh unused filter cel. A similar product could probably be made by ignition in closed vessels of the filter-cel used in the defecation of the cane juice.

LIMING AS A MEANS OF SOIL AMENDMENT.*

BY F. HARDY,

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I. Introductory.

Liming for increasing crop production has been practised since the earliest times Records show that it was known to the cultivators of the grape vine in the time of Hesiod (B.C. 1100). In the absence of scientific knowledge of the effects of liming, the crudest rule of thumb methods were used. Between the years 1850 and 1900, the development of the fertilizer industry, and the wide spread belief which grew up in those days that mineral manures could rectify most of the deficiencies exhibited by infertile soils, led to the almost total abandonment of liming as a major operation in soil cultivation. Agricultural writings up to the beginning of the present century contain but scant and indefinite reference to the practice, especially in connexion with its value as a remedy for soil sourness. The rapid strides which have recently been made in soil science have resulted in increased attention being given to the various aspects of liming.

The first accurate knowledge gained as to the effect of adding lime to the soils was in relation to the improvement it brings about in the texture of soils of high clay content, and the power which it is sometimes stated to possess in liberating plant nutrients from pre-existing supplies in the soil, or from added organic or inorganic manures Recently the subject of soil sourness has been investigated in some detail, and the accumulation of knowledge has led to a more accurate understanding of relationships between the several factors presented by sour soils and the growth of plants rooted in them.

In a previous article in this Journal[21] † the writer has attempted to review the main facts connected with the significance of sourness in soils as recorded in modern literature. The following account of the theory of liming is intended to be a sequel to that article, and is based on the conception of soil sourness therein presented.

The various substances that go by the name of lime in agriculture include the following compounds of calcium: (1) calcium oxide (quicklime, burnt lime, CaO); (2) calcium hydroxide (slaked lime, hydrated lime, calcium hydrate, $Ca(OH_2)$; and (3) calcium carbonate (limestone, coral rock, chalk, etc., $CaCO_3$). When added to any particular type of soil, lime exerts various distinctive effects, the nature of which depends on the composition of the substance (whether oxide, hydroxide or carbonate),

* Received for publication March 31, 1921.

† Reference is made by number to the bibliography tabulated as an appendix to this article.

the degree of subdivision of the material, and the amount that is added per unit area.

There appears to be no advantage in using quicklime at a soil amendment in preference to the other forms of lime, except in so far as it lessens freightage expenses because of the fact that its weight is only three-fifths of the weight of a chemically equivalent amount of calcium carbonate, and in so far as is may exercise certain distinctive effects on the micro-organic population of the soil. It is well known that quicklime rapidly becomes slaked when exposed to the action of moisture, and that both quicklime and slaked lime give rise to the carbonate when placed in contact with carbonic acid or moist carbon dioxide.

McIntire [48] in a lengthy critical and experimental study of the carbonation of quicklime has cleared up much of the vague information heretofore recorded in scientific literature. He has established the fact that the carbonation of quicklime is always preceded by the hydration of the compound according to the equations $CaO + H_2O = Ca(OH)_2$ and $Ca(OH)_2 + CO_2 = CaCO_3 + H_2O$. The two reactions may be so repaid, however, as to be considered as simultaneous. In field cylinder experiments McIntire found that 2 tons of quicklime or of slaked lime per acre of soil were converted into carbonate within five days after being mixed with the top 6 inches of soil. When slaked lime was left as a surface layer unmixed with the top soil, carbonation was even more rapid, especially during humid atmospheric conditions.

It thus appears that if a dressing of quicklime or of slaked lime is left on the surface of a soil for several days prior to inworking, the treatment is in effect an application of finely divided calcium carbonate.

The state of subdivision in which lime is applied to soils is of considerable importance, for the greater the surface area exposed by the lime to the soil and the soil solution, the greater will be the rate of reaction between the lime and the soil constituents. That this has its effect on the productivity of soils has frequently been demonstrated by field trials. Thus Kopeloff [33], after reviewing the work of other investigators in this field up to 1917, states that his own researches prove that an increase in the fineness of division of pulverized limestone is responsible for a proportional increase in the yield of red clover on soils representative of many fertile areas in the United States. He found that there was little choice between quicklime and 200-mesh limestone. He further noted that the use of ground limestone in decreasing degrees of fineness was accompanied by corresponding increases in the activity of the bacteria that cause ammonification, nitrification and nitrogen-fixation. This fact was correlated with the chemical factors involved, such as the rate of neutralization of acidity, etc.

Frear [14] also reports similar results obtained by him in experiments at the Pennsylvania Experiment Station, and by other workers at various centres both in Europe and America.*

*See also p. 170.

The various Effects which Liming Exerts on Soils and the Interrelationships that Exist between Them.

In considering the effects of lime on the soil, and consequently on the growth of plants, it would be advisable first to refer to the chemical changes that go on when calcium carbonate is brought into contact with the soil water and the soil atmosphere. In the writer's previous article[21] (p. 57) the calcium carbonate – carbon-dioxide system was described, and its ionic equilibrium relationships were discussed in some detail. It was therein shown that calcium carbonate, introduced into soils deficient in this compound, can bring about a depression of hydrogen-ions concentration in the soil solution. The occurrence of acid substances in certain soils is responsible for the presence of hydrogen-ion in the soil solution to a degree of concentration measurably in excess of that exhibited by pure water. Calcium carbonate gives rise to calcium bicarbonate when exposed to the action of carbonic acid. This bicarbonate is partly hydrolysed in solution so as to yield hydroxyl-ions. These are the agents which primarily operate in removing hydrogen-ions in acid soil solutions. Thus the presence of calcium carbonate in a soil may result in a complete suppression of hydrogen-ions, in excess of that concentration of hydrogen-ion exhibited by pure water, and even to so great an increase in the concentration of hydroxyl-ions that the soil solution comes to possess a markedly alkaline reaction. Before this can occur, however, the buffer action of certain compounds present in it must be completely overcome. [21] (p. 57)

Calcium bicarbonate in the soil solution furthermore gives rise to a greatly increased concentration of calcium-ion, for the bicarbonate is a very soluble compound and is capable of a high degree of dissociation. [21] (p. 66.)

In attempting to explain the several and complex effects which the addition of lime to soils may bring about in those soil-conditions that affect plant growth, it would appear reasonable to distinguish between the effects due to the calcium-ions and those due to hydroxyl- and to the bicarbonate-ions that are yielded to the soil solution as a result of the treatment. In reality, however, such a distinction between the specific ionic effects can scarcely be drawn, for in certain cases more than one of the ions is operative in producing a given result. The extent to which any one of the three ions—calcium-ion, hydroxyl-ion and bicarbonate-ion—participates, can nevertheless be estimated in some degree, as may be gathered from a study of the facts which will hereafter be presented.

The various effects which liming brings about in soils may be tabulated and summarized as follows:—

1. Liming frequently alters the texture of soils because of its physico-chemical action on the finer particles, causing in many cases an agglomeration of these particles with an accompanying improvement in tilth. Improved tilth leads to increased aeration, and this profoundly modifies many of the processes that go on in soils.

2. The hydrogen-ion concentration of the soil solution is depressed to a degree depending chiefly on the amount of lime added.

   The ultimate hydrogen-ion concentration of the soil solution controls to a great extent many of the processes that go on in the soil, such as the activities of the micro-organic fauna and flora, and the absorption of water and of certain ions that serve to nourish the plant.

3. Soils deficient in calcium have their calcium content increased by liming, so that plants growing in these soils may not suffer from lack of this element as an essential factor in their normal internal metabolism.

4. Calcium-ions antagonize certain other ions that are toxic to plants or to bacteria, and thus minimize the absorption of these ions in amounts liable to cause injury.

5. Liming brings about the precipitation of certain toxic organic and inorganic substances in the soil solution of certain soils by reacting chemically with them. This effect must be distinguished carefully from the antagonistic effect due to the calcium-ion as outlined in the last section.

   When present in great excess, liming may bring about an almost complete removal from the soil solution of certain ions essential to growth, and in this way may exercise a deleterious effect on fertility.

6. Calcium-ions are said to displace certain other ions, such as those of potassium from mineral silicates, and also to displace assimilable phosphate from certain other inorganic soil compounds, and in this way to increase the availability of these ions to plants.

The above-mentioned effects will in turn be considered in detail, and explained as far as possible in the light of modern knowledge. The results of recent experiments, performed both in the laboratory and in the field, that have bearing on the facts mentioned will be reviewed, and an attempt made to correlate the data, so that a comprehensive idea of the intricate and complex effects of adding lime to the soil may be obtained.

It is not to be supposed that the addition of lime to any particular soil, produces in any definite order effects such as those named in the above list. One cannot say, for example, that excess of lime applied to a sour clay soil will in every case first neutralize the acidity and then flocculate colloidal substances present, or that it will first bring about flocculation and then neutralization. In most cases the various effects of liming are produced simultaneously ; but there is evidence to show, however, that in certain instances the effect of liming is to bring about its distinctive results in some definite sequence.

The whole question of the changes that occur when soils are limed is one of the adjustment of equilibrium in a complex system containing many interrelated factors. Any change in external conditions will effect this equilibrium, and readjustments will follow. The complexity of the reactions that proceed in soils of different types when lime is added to them explains in some measure the discrepancies that have arisen in liming

experiments. Sufficient care has not been taken in all cases, carefully to distinguish between the various phases of the problem, in particular the relation of the plant to the soil.

Investigations into the specific effects of liming present the same difficulties, and are open to the same objections as various other kinds of biological experimentation, for it is almost impossible to control all the variable factors presented by the soil-plant system during a study of any single factor which is directly under observation.

It is only by means of a thorough understanding of the numerous effects that lime exerts in the soil, however, that the particular problem can be solved, of why, when, and how a given soil should be limed with a view to increasing its productivity.

1. THE EFFECT OF LIMING ON SOIL TEXTURE.

The improvement in tilth which liming brings about in clayey soils is given great prominence in all writings on soil management. Much research work has been carried out to find an explanation of the mechanism of this effect of liming, and to attempt to discover the quantitative laws that underly it.

The progress of colloid chemistry has furnished many data which have thrown light on the phenomenon of coagulation or flocculation of the finer particles of the soil as brought about by certain substances. It has long been known that salts and acids (electrolytes) added to colloid dispersoids cause coagulation. The reason for this has been referred to the changes in electrical state of the dispersed particles caused by their adsorbing certain ions yielded by the ionic dissociation of the electrolyte. It has been supposed that clay particles, for instance, are negatively charged when suspended in water, and for this reason each particle repels every other similar particle, so that aggregation is prevented. When the particles adsorb positively-charged ions, however, their negative charges are neutralized; the isoelectric point is thus reached, and the particles are now no longer kept apart by electrostatic forces. Surface attraction or cohesion is able to operate, and aggregation ensues.

In order to gain some knowledge of the properties of colloidal substances in soils, numerous experimenters have studied suspensions of kaolin and of other naturally occurring clays. As early as 1886, or only a few years after the publication of Graham's classical researches on colloidal substances, Schulze recorded results on the calcium and magnesium salt requirements for flocculation of clay suspensions. Hilgard in 1877 also studied the effect of lime on the texture of clays. Later it was claimed by several investigators (for example, Schulze in 1882 and Spring in 1900*) that the flocculating power of a salt depends on the valency of the metal present in it. The ratio 350:20: 1 was developed by Schulze as representing the relative coagulating powers of trivalent, divalent, and monovalent metallic ions, respectively.

Hall and Morrison[20] studied the efficiency of various acids and salts on the flocculation of kaolin suspensions. With the

commoner acids they found that order of efficiency to be $HCl > HNO_3 > H_2SO_4$, and for certain metallic ions $Al > Ca > K > Na$. Wolkoff[57] investigated the flocculation of several, soils, and showed that the flocculation efficiency of any given soil on salt suspensions varies with the chemical constitution of the soil, and that Schulze's valency law did not hold true for the soils studied. Humic substances were found to hinder the coagulating power of the flocculating agent.

The valency law is nowadays regarded as unsubstantiated, for certain recent researches have revealed cases in which the relationships between the precipitancy power of ions is not even in approximate agreement with that between their valencies.

So far the flocculating action of electrolytes has been referred chiefly to their electro-positive ions, for instance, the metallic ions deliberated when salts dissociate. The results now to be present indicate that the electro-negative ion is also effective in regulating the degree of agglomeration which colloidal substances in soils may suffer when brought into contact with electrolytes. The phenomenon has long been known, but little experimental work has been recorded on this phase of the subject. Comber[9] has recently described interesting experiments on the flocculation of soils, in which he points out that, in any attempt to correlate the flocculation of soil particles with the established facts of modern colloid chemistry, attention must be paid to the complication of the soil system. There are two obvious causes of complication, each of which will have an important bearing upon the action of electrolytes in the soil ; first, the soil particles are protected by organic and inorganic colloidal substances ; and second the soil is a system of particles of all degrees of size.

Comber's experiments were carried out with silt, clay, and soil. The flocculation of these in solutions of neutral and of alkaline reaction was studied. It was demonstrated first of all that alkalinity decreases the flocculating effect of calcium-ion on *silt*. This appears to be in full accord with the electrical theory of flocculation as outlined above, for, if we assume the silt particles to possess negative charges, and their flocculation to be due to the neutralization of these charges as a result of the adsorption of positively charged calcium ions, it follows that, when the silt particles also adsorb negatively charged hydroxyl-ions, in addition to the positively charged calcium-ions, the flocculating power of the latter becomes reduced. Hence calcium hydroxide is not so good a flocculant for silt as calcium bicarbonate or calcium nitrate.

Comber found, however, that the effect of alkalinity on *clay* presented quite another case. Here the presence of hydroxyl-ions is observed to increase the flocculating effect of calcium-ion. Thus calcium hydroxide is a better flocculant for clay than neutral calcium salts.

Comber explains this difference between silt and clay by assuming that the colloidal state of the two is widely different. Colloid chemists have long distinguished between the colloidal state exhibited by such substances as silicic acid and the gums, which are not easily coagulated by electrolytes, and which are able to absorb water in large quanties, and non-gelatinizing

substances which are easily coagulated, and which exhibit no marked tendency to absorb water and swell. The two classes o substances have been referred to as emulsoid and suspensoid substances, respectively. According to this nomenclature, clay is to be regarded as an emulsoid, and silt as a supensoid substance.

It has repeatedly been demonstrated that, in the case of the emulsoid colloids, the importance of the electrical state is not so great as in the case of the suspensoid colloids. The electric charge associated with the former is frequently accidental and less characteristic. In some instances its sign may be reversed simply by altering the reaction of the medium in which the emulsoid colloid is held.

It seems highly probable that the clay particles of a soil are protected or covered by some such emulsoid substance as silicic acid or a complex of organic substances belonging to the so-called humus component of the soil. The physico-chemical properties of the particles will be coincident with those of the protecting emulsoid material. This will account for the differences that have been noted in the colloidal properties exhibited by kaolin and by soil clay, as has already been indicated (See Wolkoff[57] p. 587.)

The action of calcium hydroxide and of calcium carbonate as flocculants of clay has generally been regarded as anomalous, for it has usually been taught that alkalies are deflocculants of clay, whereas it is known in practice that these two calcium compounds usually behave very effectively as flocculants. If the emulsoid character of true clay is admitted, then calcium hydroxide is seen to be an ideal flocculant, for the calcium-ions and the hydroxyl ions are not working in opposition but in co-operation. The hydroxyl ions remove the emulsoid from its isoelectric point, and thus render it less stable; the calcium-ions then coagulate the unstable emulsoid.

Comber suggests that clay – itself a protected colloid—functions in the soil as a protective col'oid. Siliceous and organic emulsoids appear to protect the clay particles, and the clay appears to protect the silt. Hence fine silt soils are not flocculated by calcium hydroxide on account of the insufficiency of the relatively small amount of emulsoid clay to protect the large surface exposed by the fine silt. True clay soils, on the other hand, are readily flocccculated by calcium hydroxide because the emulsoid characters of the clay predominate in the soil. In this way many of the perplexing irregularities in the observed effects of liming on the texture of different types of soils may be explained.

Non-flocculated clay soils are notoriously non-permeable, and for this reason oxidation in them is usually lacking. Aerobic bacterial activity is low, and plant residues decay in such a way that acidic and toxic organic compounds tend to accumulate. The soils thus become sour and unproductive. The clay land farmer experiences exceptional trouble in bringing clay soils into cultivation. His chief aid is liming, for this brings about flocculation of the true clay particles, as has been described above Good aeration follows on good tilth. Beneficial microorganisms become profilic; toxic and acidic organic compounds

are oxidized and rendered innocuous, and a high state of fertilite is induced.

That liming actually does bring about in the majority of cases the sequence of changes indicated, has repeatedly been proved in farming practice. The various stages have also been demonstrated in numerous field experiments which have been laid down to compare the effects of liming upon crop yield, or upon the rate at which various soil processes go on. Whilst it is well nigh impossible in agronomic experimentation to distinguish between, and to measure, the many ways in which liming improves soil conditions, there is no doubt that the improvement in tilth which liming induces is one of the chief benefits of the treatment. Thus Neller [47] in examining the effect of liming on the processes of oxidation (as measured by the rate of evolution of carbon-dioxide), of ammonification and of nitrification in the heavy loam soils of the New Jersey Experiment Station, points out the improvement in tilth that liming has brought about in the soil of certain plots, and correlates this with the increased oxidative power of the limed soils.

2. THE EFFECT OF LIMING ON SOIL REACTION.

a. Soil acidity and plant growth.

The several inhibitory effects which an excessive concentration of hydrogen-ion in the soil solution exerts on soil conditions and plant growth have been fully discussed in the article on soil sourness already cited[21]. Perhaps the most important of these is its effect on micro-organic life. Soil acidity affects the micro-organic fauna and flora of soils in different specific ways. Whereas the bacteria and fungi that are responsible for the formation of ammonium salts from nitrogenous organic compounds present in plant residues are apparently but little affected, even by considerable acid intensity, the bacteria of nitrification and of nitrogen-fixation are very sensitive to hydrogen-ion, the activity of the latter in particular being markedly reduced by a medium whose pH value is below 6·0 ([21] p. 61). Nodule bacteria, which fix atmospheric nitrogen when they are growing in symbiosis with the roots of leguminous plants, exhibit different degrees of susceptibility to hydrogen-ion, depending on the particular strain of bacterium. The limits of acidity for the various strains that characterize different leguminous plants of cultivation vary between pH 3·15 and pH 4·9, so that nodule bacteria, on the whole, seem able to withstand a considerable concentration of hydrogen-ion in the soil solution.

Certain plant disease organisms appear to be susceptible to the toxic effect of hydrogen-ion, or conversely to that of hydroxyl-ion[21] (p. 65). Whereas a number of them can withstand an appreciably high degree of hydroxyl ion concentration, others are markedly susceptible to it.

The effect of hydrogen ion on the germination of seeds[21] (p 61) seems to vary with the species of plant that produces the seeds, for some seeds germinate more rapidly when exposed to acid conditions, whereas others respond more readily to alkaline conditions.

The growth of plants appears to proceed best under slightly acid conditions[21] (p. 62), possibly because the absorption of ions which plants need for their nourishment is accelerated in a medium of apppreciable acidity. Possibly also water absorption is controlled to some extent by hydrogen-ion concentration. Dachnowski[12] showed that water absorption is diminished by acidity, but further research is needed before any definite relationships can be finally established between the rate of water imbibition and plant growth.

b. Field experiments on liming in relation to reaction.

Numerous field experiments have been conducted in various parts of the world to test the relationship between soil reaction and the various soil processes involved in the growth of plants.

In considering the effect of lime on the different soil micro-organisms that are responsible for the several stages of decomposition that commence with the breaking down of the complex nitrogenous organic compounds present in plant residues and end in the formation of nitrates, it would be best first to consider the production of humus in soils.

(a) The extent of our knowledge as to the composition of humus and the chemical changes that are responsible for its formation from plant residues in soil is still very limited.* General experience has indicated that the maintenance of an abundant supply of humus in the soil is one of the first essentials of successful field management Thi- humus must be of the type that is formed under conditions of good aeration ; it must not contain an excess of acidic compounds or of toxic substances. The presence of lime in the soil seems to be an important factor in the complex chemical changes that are in the main controlled by micro-organic activity, and that result in the formation of a desirable kind of humns.

The rôle of lime in the soil, as a factor in humus production and in the subsequent changes that go on when humus is decomposed, is not usually clearly defined in text books on agronomy. Various statements occur to the effect that lime acts as a ' conservator ' or, *per contra*, that it acts as a destroyer of humus. The relative effects of the different forms of lime have also been discussed at great length, and numerous experiments have been described in support of one or other of the various opinions.

Frear [14], (1915, pp. 143-58) gives a detailed account of many such field experiments. His conclusions are worthy of citation. (1) ' From all the facts now in our possession humus formation and decay are due chiefly to the action of lower organisms inhabiting the soil.' (2) ' The general result of experiments is that the addition of carbonate of lime increases the rate of bacterial decomposition in the soil,' . . . . . except when this dressing is added in too large amounts.' (3) ' The effect of quick-lime . . . . is a short-time decrease of bacterial and other soil life, followed ere long by a large increase in the number of these organisms and in their activity.' (4) ' Where the conditions of soil composition and reaction are such as to induce an increase

*See, however, the recent work of Beckley, *Journ. Ag. Sci.* XI, 1921, p. 69.

in bacterial life and vigour as the consequence of a lime dressing, we should expect an increased rate in humus decomposition to follow. Liming an acid soil should show such results; but liming a soil already alkaline might have little effect.' (5) 'The evidence from the more critically planned investigations does not warrant any sharp distinction between lime in the caustic (i.e. quicklime) and carbonate forms as respects their *ultimate* direct effects upon humus decay. *

Whereas these conclusions are probably true in the main various investigators have reported differences of some importance between the effects of quicklime and of calcium carbonate on the soil reaction, and consequently on micro-organic life. Thus Hutchinson and McLennan [29] have claimed that quicklime, when applied to soils brings about partial sterilization effects comparable with those produced by antiseptics and heating. In order to discover the precise chemical changes induced in the soil system through the addition of different forms of lime, Hoagland and Christie [37] followed in the laboratory the changes that went on in the hydroxyl ion concentration of three distinct types of soil, firstly after calcium oxide, and secondly, calcium carbonate, has been added to them. Hydroxyl-ion concentration was measured by the use of the hydrogen electrode. The results showed that a great increase in the hydroxyl-ion concentration occurred immediately after the addition of quicklime to all three soil types, the effect being most marked with a sandy soil. Calcium carbonate gave similar results, but much lower concentrations of hydroxyl-ion were recorded. Within three days a great decrease in alkalinity had taken place in all the soil samples. This decrease was continued slowly for more than six weeks afterwards. The investigators suggest that the partial sterilization effects which Hutchinson and McLennan observed when quicklime is added to certain soils may be due to the initial high hydroxyl-ion concentration which quicklime produces, and which is markedly toxic to many soil micro-organisms, especially protozoa. Furthermore, they point out the possibility of a deleterious effect of quicklime, if added in too great amount to soils, in that it might bring about an almost complete inhibition of nitrification.

(b) Proceeding now to a consideration of the effect of liming on the *formation of ammonium compounds* from the nitrogenous compounds present in humus, it should be remembered that ammonification is apparently not markedly depressed by acid soil conditions. It would appear that the organisms responsible for ammonification have a very wide range of acid tolerance. Nevertheless experiments have shown that liming greatly increases the production of ammonium compounds in soils. Thus Peck [49] found that lime added to sugar-cane lands in Hawaii stimulated ammonification of the soil organic nitrogen. Frear [14] (p. 137) has recorded numerous similar observations.

(c) As regarding *nitrification*, we should naturally expect

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*Considering that quicklime is rapidly hydrated and carbonated when applied to soils (see p. 162), the specific effect of quicklime, if any, cannot be exerted for any great length of time.

liming to have a marked effect in accelerating the rate of production of nitrates from ammonium compounds in soils, for the bacteria of nitrification are very intolerant to acidity, and any decrease in hydrogen-ion concentration at once favours their multiplication. The results of an enormous number of field experiments have borne out this surmise. Noyes and Conner [48] have citied many instances where liming has been followed by increases in nitrate formation in soils. Their own experiments with typical acid soils that received dressings of calcium carbonate and of various mineral fertilizers, showed that calcium carbonate in all cases markedly increased nitrification in the acid soils, whereas fertilizers alone had little effect in this direction. Upon the same subject Frear [14] (p. 159) writes : 'It is clear that the use of lime . . . . upon an acid soil increases ammonification and nitrification. Its tendency therefore is to hasten the rate of decline in nitrogen content common to all cultivated lands, unless special methods of management, cropping* or fertilizing are used to maintain the supply.'

In connexion with the last point raised, Fred and Graul [15] found that, although liming stimulates nitrate formation at first, later the reverse is true, and that a decided decrease occurs, at least in the soils investigated by them. This result they attribute to the activity of denitrifying bacteria in the soils examined.

(d) That *nitrogen fixation* by free-living organisms in the soil is also increased by liming has been proved by Ashby at Rothamsted. Ashby [2] showed that the use of lime on certain arable soils has more than doubled the fixation of nitrogen by *Azotobacter.* Loew[38] states that liming has favourably affected *Azotobacter* development in the acid soils of Porto Rico, except where the soil texture has been such as to exclude oxygen of the atmosphere. These examples are but few from a large number of experiments on this aspect of the subject. (See Frear[14] p.141.) The results have been practically the same in all cases.

(e) Field trials on the effect of liming on the *assimilation of nitrogen by nodule bacteria* living in symbiosis with certain leguminous plants have also been carried out in recent years. Thus Lipman and Blair[35] at the New Jersey Agricultural Station have studied in the first place the effect of liming on the yield of non-leguminous plants, and have shown that limed plots lost nitrogen at a considerably greater rate than unlimed plots With leguminous plants, on the other hand, the soil of the limed plots was appreciably enriched in nitrogen as compared with the unlimed plots. This was interpreted as indicating the beneficial effect which liming produces on the activities of the nitrogen-fixing bacteria that live in symbiosis with the leguminous plants.

Fred and Graul [16] at Winconsin University also have found that the soil of limed plots growing soya beans and red clover exhibits an increase in the amount of nitrogen fixed from the atmosphere over that gained by the soil of unlimed plots.

(f) It is unnecessary to review in this article the numerous experiments that have been performed in connexion with the

*Such as the inclusion of leguminous plants in the rotation practised.

control by liming of certain *plant disease organisms* that pass, at least part of their lives in the soil. Suffice it to state that liming has long been advocated as one of the remedial measures to be tried in attempts to combat such diseases. In certain cases small dressings are apparently sufficient to limit the activities of the organisms because of their effect in reducing soil acidity. In most cases, however, large dressings are prescribed, and moreover, the form of lime to be used is definitely restricted to quicklime or slaked lime. The effects of such dressings may primarily be similar to those already described in connexion with partial sterilization of soils.

The deleterious effect on the *growth of the seedlings* of certain plants of excessive hydrogen-ion and hydroxyl-ion concentrations has been demonstrated by a limited number of nutrient culture studies to which reference has been made in the writer's article on soil sourness [21] (p. 61). Important in this connexion is the work of Hoagland [26] who found that for barley, the hydroxyl-ion is more toxic than the hydrogen-ion of the same concentration. For the nutrient solutions used, Hoagland showed that a concentration of OH-ion greater than $1{\cdot}8 \times 10^{-6}$ (pH = 8 4) was distinctly injurious, and, when exceeding $2{\cdot}5 \times 10^{-5}$ (pH = 9·5) extremely toxic to the growth of barley.

Joffe [31] adjusted the reaction of a sample of New Jersey loam soil by adding different amounts of dilute sulphuric acid or of calcium carbonate, and in this way obtained twenty soil cultures with reactions varying between pH 3·0 and 7·1. He then grew alfalfa (lucerne) from seed in each culture, and after about six months, ascertained the differences in the weights of the harvested dry crops, as well as the nitrogen percentage content of the tops. In this way he was able to demonstrate that the yield of lucerne tops showed a gradual increase with an increase in the pH value of the soil solution. Germination was found to be checked in the more acid soils, but when once established, the seedlings grew well, even in soils whose pH value was as low as 3·8. Nodule formation was least in soils of lowest pH value and correspondingly, the nitrogen content of plants grown in the more acid soils was lowest. Root development, however, was found to be greatest in the more acid soil cultures.

Quite recently, Salter and McIlvaine (see [21] p. 62), in their studies on the effect of the reaction of nutrient solutions on the germination and growth of certain commonly cultivated plants, have shown that an alkaline reaction is more harmful to these processes than an acidity reaction. There would thus appear to be actual danger in over-liming, a conclusion the force of which will further be demonstrated in another connexion. (See p. 176).

3. LIMING TO CORRECT DEFICIENCY IN CALCIUM IN CERTAIN SOILS.

The important rôle which calcium plays in plant metabolism has been discussed in some detail in the writer's article on soil sourness [21], (p. 66). It is unnecessary to reconsider the question in this place. Suffice it to state that liming is the most obviou

remedy for deficiency in calcium that may be the direct cause of the infertility of certain soils.

4. THE ANTAGONISTIC EFFECT OF CALCIUM-ION IN THE SOIL SOLUTION.

That the presence of certain salts in nutrient solutions in which plants are growing influences the specific effects produced by other salts has long been recognized. A great number of experiments have been performed to determine as definitely as possible the nature of this mutual influence, and an immense literature dealing with the results of such experiments has accumulated.

The laws governing the absorption of salts, or more strictly the absorption of ions, are little understood, and the exact mechanism whereby ions enter the plant has not as yet been definitely elucidated. It appears, however, from the researches of certain physiologists, notably Pauli, Szucs and Loeb (see [55]) that the semi-permeable membrane which separates the root cell sap from the soil solution plays a very important rôle in absorption. Various ions present in the soil solution are supposed to be able to form absorption complexes with the colloidal substances of which the membrane is composed, and by a reversal of this process, the ions enter the cell. When several ions are being conveyed into the cell by the same unit of the plasma membrane, the entrance of each is hindered by the others, and thus an antagonism arises.

As long ago as 1859, Sachs noted in nutrient culture studies that plants grow best when a certain balance is maintained between the various constituents of the solution. In 1875, Boehm observed that the toxicity produced by certain salts, when present alone in nutrient solutions, could be lessened or eliminated by small quantities of calcium salts. By numerous experiments along similar lines it has been shown that calcium-ions are able to counteract the toxic effect of an excessive concentration of such ions as those of magnesium, potassium, sodium, ammonium, barium, strontium and manganese (McCool).[40] Mutual antagonism between various combinations of pairs of these ions has also been demonstrated, and of all the elements tried, calcium-ion has been found to be the most effective in preventing injury by the action of the other ions named.

The necessity for the existence of an exact ratio between the concentrations of mutually antagonistic ions in nutrient solutions for optimum plant growth has been maintained by Osterhout[3]. Whereas recent work has in some measure borne out this assumption, it has been shown that for certain plants at least a fairly wide range in the rations of ionic concentrations is tolerated without any marked reductions in plant growth. Recent research has further indicated that the optimum ratio between ions not only varies for different plants, but also for the several growth stages of each species of plant.

Before ideas on antagonism had taken a definite form, Loew [37] elaborated a theory to account for the toxic properties of magnesium when calcium was not present in the nutrient

solution in sufficient quantity. His theory was based on the assumption that certain modifications in the chloroplasts and protoplasm of plants were produced when magnesium and not calcium was available in the nutrient solution. The theory assumes that the seat of antagonism between calcium and magnesium lies within the plant cell and not at its surface, as is nowadays generally believed. Loew considered that plants require a definite calcium-magnesium ratio for optimum growth, and assigned a value of 1:1 to this ratio in the case of cereals. with a larger proportion of calcium for other more leafy plants, This conclusion has been questioned, however, by more recent investigators.

In attempting to apply the results of nutrient solution studies on the antagonistic effects of ions on one another to the actual conditions that obtain in the soil, it is obvious that the number of influencing factors to be considered in soil studies becomes vastly greater. The components of different soils react in very different ways, when brought into contact with any given salt solution. The final balance that exists in the soil solution between the various ions derived from the compounds present in the soil, or from compounds introduced in manures and fertilizers, is the result of a highly complex series of interrelated reactions. In particular, the effects of an increased concentration of calcium-ion that follows on liming in minimizing or eliminating the toxicity due to excessive concentration of ions such as those of magnesium, sodium, aluminium and manganese, is a factor of im portance in plant nutrition.

In practice, however, it is hard to gauge this effect, and although many field experiments have been devised to test the application of the principle of antagonism to actual crop production, few definite results have yet been obtained. For example, numerous investigators have sought answers to the Loew theory of a calcium magnesium ratio as applied to soils and liming, with just as numerous and conflicting results. A review of the work of the more noteworthy of these attempts is given by Wyatt,[58] whose own experiments with certain cereals and leguminous crops, grown in various types of soil to which different kinds and amounts of calcium and magnesium compounds were added, indicate that ratios of calcium to magnesium within rather wide limits give no marked differences in yield. There would appear, therefore, to be little fear of injury attached to the use of low-grade potash fertilizers rich in magnesium salts, or of magnesian limestone as s il ameliorants, which is against the view previously held by many agronomists (see [14], pp. 191-201).

A recent investigation by Greaves[19] is worthy of record. This worker attempted to discover the extent of the antitoxic action of various calcium and iron salts towardsother compounds, when applied to a typical Utah arable soil. Solutions of the salts were added to the soil in definite amounts, and the effects on ammonification and nitrfiication were quantitatively estimated. The multiplicity of results is too great to be recorded in full in this place, but it may be mentioned that indications were obtained that the non-metallic ions, as well as the metallic ions yielded by the salts, exerted antagonistic effects one on the

other. Calcium-ion was especially found to be antitoxic to various other ions, at least so far as ammonification and nitrification are concerned.

Although Greaves' work does not throw further light on the direct relationship in the soil between antagonism and absorption by the roots of higher plants, yet it has some bearing on the question of fertility, and on this account is worthy of mention.

5 THE EFFECT OF LIMING IN PRECIPITATING CERTAIN TOXIC ORGANIC AND INORGANIC SUBSTANCES IN THE SOIL SOLUTION.

(a) *Precipitation of toxic organic substances.*

The widely-discussed question of the rôle which certain complex toxic organic substances play in soil infertility has led to a reconsideration of the mechanism of the action of fertilizers. Those who hold that infertility is due, in the main, to the presence in soils of toxic organic compounds, ascribe the beneficial effects of manuring to its ability to counteract these toxins. In particular it has been demonstrated by culture experiments that calcium carbonate is an effective agent in decreasing the toxicity of certain organic compounds.

Thus Breazeale[6] in 1906, and Livingston[36] in 1907 showed that water extracts of certain unproductive soils were greatly improved by the addition of calcium carbonate, and were thereby rendered capable of supporting healthy plants. Schreiner and Skinner (see[21], p. 76) found that toxicity of salicylic aldehyde to wheat seedlings growing in nutrient media was decreased by the addition of calcium carbonate to the cultures. Many other investigators have demonstrated that the deleterious effect on plant growth of certain acidic products of the decay of plant residues and of definite root excretions may be counteracted by neutralizing the culture media containing these substances with calcium carbonate (see[21], [76] Rigg; Dachnowski).

The mechanism of the antitoxic effect of calcium carbonate in many of the experiments described in the literature on the subject, both those in which nutrient culture media and those in which actual soils were used, is not in every case quite clear. In those instances where the toxic organic compound is a definite acid, such as dihydroxystearic acid, it is easy to understand that neutralization by means of lime might give rise to a harmless calcium salt or to an insoluble product which is incapable of being absorbed by plant roots. Probably the beneficial effects ascribed to the direct chemical action of calcium carbonate, especially in connexion with actual soils, are in reality due to the general improvement of the environmental conditions, in that the oxidative power of the medium is increased by the addition of lime, or the development of bacteria responsible for the destruction of the toxic compounds is encouraged.

(b) *Precipitation of toxic inorganic substances.*

It was noted by Ruprecht and Morse[52] in their culture studies with aluminium and iron sulphates, that the addition of calcium carbonate to the cultures eliminated the toxic effect

of the ions of these metals. This result they explained as being due to the removal of the toxic metallic-ions by their precipitation as hydroxides.*

Mirasol[45] in his comprehensive investigation into the significance of aluminium as a factor in soil sourness (see[21], p.70), also demonstrated the antitoxic effect of calcium carbonate when introduced into sand cultures of clover which were treated with solutions of salts of aluminium. Mirasol, however, considered that the calcium carbonate precipitated the aluminium, not as hydroxide, but as the much more insoluble calcium aluminate. Similar results were obtained when calcium superphosphate (acid calcium phosphate, $CaH_4(Po_4)^2$), was substituted for calcium carbonate, but in this case it was assumed that the precipitation of the active aluminium is due to the formation of insoluble aluminium phosphate.‡

The removal of aluminium from the soil solution by liming (or phosphating), which may be assumed to take place in those cases where an excessive concentration of aluminium-ion occurs must be carefully distinguished from the antagonistic effect that calcium-ion exerts in minimizing the absorption of aluminium-ion by the plant root, as described in the last section.

In the majority of cases of sour soils that contain an excessive concentration of aluminium-ion in the soil solution the effect of increasing the amount of dissolved bicarbonate by adding lime to the soil is primarily to precipitate the aluminium. Simultaneously and collaterally with this, the increased concentration of calcium-ion opposes the entry of aluminium-ion into the plant root cells. This latter effect may obviously only become significant when the aluminium-ion concentration reaches a low figure.

As regards iron and manganese, liming may confidently be expected to remove excess of the former when it occurs in high concentration in the soil solution, for the properties of iron compounds are very similar to those of aluminium compounds. In the case of maganese, Mirasol (*loc. cit*) found that calcium carbonate introduced into sand cultures treated with solutions of manganese salts had little effect in precipitating the metal.

(c) *Effects of an excessive lime content in soils.*

It is possible to imagine that an excessive concentration in the soil solution of calcium bicarbonate, and of the ions yielded by this compound when it dissociates, might precipitate practically completely all the aluminium and iron that is present in solution. Since all plants require iron as an element essential

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*$3\,Ca(HCO_3)_2 + Al_2(So_4)_3 + 6H_2O = Al_2(OH)_6 + 3\,Ca\,So_4 + 6H_2\,CO$

†$4\,Ca(HCO_3)_2 + Al_2(SO_4)_3\,C\,4\,H_2\,O = Ca\,O.\,Al_2\,O_3 + 3\,CaSO_4 + 8H_2CO_3$

‡$Ca\,H_4\,(PO_4)_2 + Al_2\,(SO_4)_3 = 2AlPO_4 + Ca\,SO_4 + 2H_2\,SO_4$.

††Numerous investigations have been carried out on the toxicity to plant growth of such inorganic substances as salts of copper and arsenates (see Trouq and Sykora, *Soil Science*, III, 1907, p.333). They are not of sufficient general importance to warrant record in this article.

to the production of chlorophyl, it might follow that the almost complete precipitation of iron by calcium carbonate, coupled with a marked antagonism to its entry into the root cells, wolud result in some functional derangement which would become symptomatic in plants growing under such special conditions. That this result does actually happen when a soil contains a great excess of calcium carbonate is indicated by recent researches into the causes of lime-induced chlorosis in plants.

Plants growing in soils very rich in calcium carbonate frequently are characterized by a yellow or pale-green leaf-colour which stands out in marked contrast to the dark-green tint normally exhibited by the plants. Thus grape-vines growing on certain limestone soils in France often show this peculiarity, and sugar-cane, rice, maize and other cereal grasses, pine-apple, pear, apple and citrus fruit trees also exhibit similar appearances associated with the same soil condition. The name 'chlorosis' has been given to the affection. There are other causes of chlorosis, besides the one already mentioned, but these will not be discussed in this place.

Plants that suffer from lime-induced chlorosis frequently contain in their leaves abundant crystals of calcium oxalate. Despite the removal of large amounts of calcium from the plant sap thus indicated, the sap is neutral or alkaline in reaction instead of normally slightly acid. At first sight therefore, lime-induced chlorosis would appear to be the result of excessive alkalinity in the plant sap produced by over absorption of calcium-ion.

Gile and Carrero[18], in a critical study of the cause of lime-induced chlorosis in certain plants, showed, however, by analysing the ash of chlorotic leaves, that a deficiency in iron is usually associated with the chlorotic condition, with possibly an excess of calcium as a contributing factor. Chlorosis was found to be remedied to some extent by spraying the leaves of chlorotic plants with iron sulphate solution. Numerous experiments with the rice plant indicated that rice is not very sensitive to the presence of excessive amounts of calcium carbonate in the soil, but is markedly sensitive to depression in the availability of iron which such excess produces.

Although the causal relationship between calcium carbonate and the low availability of iron in soils containing excess of lime is indicated by Gile and Carrero's investigations as the major factor in certain examples of chlorosis, the simple explanation of the precipitating and antagonising effect which lime exerts on iron in nutrient solutions as described above apparently does not completely fit the case when applied to actual soil conditions. Gile and Carrero showed that the presence of organic matter in soil in some way affects the availability of iron in highly calcareous soils, as does also the presence of free water and clay substance. The whole question is therefore one of considerable complexity. It may at least be concluded that liming may become a real danger if carried too far, especially in the case of dry sandy soils not over rich in organic matter.

6. THE POSSIBLE INDIRECT FERTILIZING EFFECT WHICH LIME MAY BRING ABOUT IN CAUSING AN EXCHANGE OF IONS WHEN ADDED TO SOILS.

The effect which liming produces on the water-soluble nutrients of soils has been the subject of a great deal of experimentation. The prevailing idea has been that liming renders more available certain elements, such as potassium, magnesium, and the phosphate radicle, because of the interchange of ions that is presumed to go on between the added lime and certain mineral components of soils*. Certain experiments, however, seem to refute this theory.

(a) *Potassium.*

Let us first consider the case of potassium. Several laboratory experiments on the effect of lime on potassium-bearing minerals, such as orthoclase felspar, have been carried out by various investigators. Thus Brigg and Breazeale[7] found that powdered orthoclase, as well as soils containing this mineral, caused no increase in water soluble potassium, when shaken with a solution of calcium carbonate on several soil-forming minerals The results of his experiments show that calcium bicarbonate solution possesses no power to unlock potash from any of the minerals tried.

Whilst the majority of experimenters have obtained results concordant with the above, Morse and Curry[46] found that lime increased the solubility of potassium in felspar, but that this effect may not be observed when soils are similarly treated, because of the simultaneous removal of the liberated potassium owing to the adsorbtive power of colloidal clay.

Andrè[1] noted that glauconite (a hydrated silicate of aluminium iron and potassium), yields part of its potassium when treated with calcium carbonate.

Theoretically, by the principle of basic exchange, it is possible that salts of calcium, including the bicarbonate, might react with potash minerals so as to liberate potassium-ions to the soil solution. According to the adsorption idea of basic exchange, the calcium-ions set free by dissociation of a neutral calcium salt added to soil are absorbed by certain soil colloidal substances, and the free acid is liberated. (See[21], p. 67.) This acid is then able to attack potassium-bearing minerals, and thus to bring about an increase in the potassium-ion concentration in the soil solution. It is conceivable, however, that carbonic acid (which is the acid corresponding to calcium bicarbonate) is too weak an acid and is liberated in too small amount to decompose the commoner potassium-bearing minerals in the soil, so that one is able to explain in this way the negative results obtained by the majority of investigators who have studied the reaction between lime and certain potash minerals.

Bradley[5] showed that lime did not act as an indirect fertilizer when applied to soils in the laboratory, although gypsum gave an increase in the water-soluble potassium of the extracts

*See for example, Hall, 'TheSoil.' LondonMray ,'Johur1918, p. 262. Also Hilgard, "Soils.n ,New York. Mcamillan, 1918, p. 379.

Christie and Martin[3] set out to discover by a series of laboratory experiments possible reasons for the apparent disagreement between investigations on the question of the indirect fertilizing action of lime. They studied the chemical effects of calcium oxide and of calcium carbonate on the water-soluble nutrients of several soils belonging to three distinct types. Water extracts of the limed and unlimed soils were analysed, and the amounts of calcium, magnesium, potassium, phosphate, sulphate and nitrate were compared in them at various periods. Supplementary data by freezing point and electrical conductivity methods were also obtained. The results of this research show that all soils do not react chemically with lime in the same manner, and further, that even the same soil under different concentrations of soil solution, due to cropping or fallowing, may react differently. It is difficult to understand the reason for these facts; evidently the addition of lime changes the equilibrium in the soil solution, and the resultant effects are variable. It would thus appear to be impossible to predict what the effects of liming will be as regards increasing or decreasing the availability of nutrient elements in any particular soil. Only actual trials with the soil in question could be hoped to yield definite information as to these effects.

As an interesting example of an extensive investigation into the effect of liming on the availability of potassium under field conditions, the work of Mc Intire[44] at the Pennsylvania Experiment Station in 1911, and at the Tennessee Station in 1914-19, is worthy of record. McIntire tabulated a number of systematic analyses of the leachings that collected in lysimeters into which the water from two types of limed soils contained in large tanks was allowed to drain. The results showed that the original free soil-water leachings were richer in potassium salts than they were when they become impregnated with calcium bicarbonate. No indications were obtained to suggest that lime so altered the original form of the soil-potassium as to render any portion of it more available or beneficial to plant growth.

These results are in perfect agreement with those of earlier but similar studies undertaken by Lyon and Bizzell[39] at the Cornell University Experiment Station, and coincide in general with the findings of many other workers in various parts of the world. In certain cases, noteworthy exceptions have been recorded in which liming has been found to increase the potassium content of the soil solution. These exceptions are in most instances susceptible of elucidation by considerations of local peculiarities of rainfall, soil-type cropping or temperature-range, all of which must have their bearing on the extent of the potassium outgo from the soil.

The chemical analyses of wheat furnished by Gaither[17] and by McIntire[41] indicate a depressing effect on the absorption of potassium when wheat crops are grown on limed soils. This result has also been noted by other investigators for other species of silicicolous plants, and it has long been known that such plants respond most markedly to potassic manures when growing on soils rich in calcium carbonat

(b) *Phosphates.*

As regards the effect of lime on phosphates in the soil, it appears from numerous experiments that there is some possibility of lime increasing the availability of this important soil component under certain specific conditions. Thus Hartwell and Kellog [23] found that liming considerably increased the yield of turnips at the Rhode Island Experiment Station, and that the percentage of phosphorus in the dry-matter of these plants was greater than in that of turnips grown in unlimed soil.

The Rhode Island soils, however, are markedly acidic in reaction, and contain appreciable excess of aluminium and iron-ions in the soil solution. It appears probable in this case, and in most other similar cases, that the beneficial effect of liming is due to the interaction between the lime and the aluminium and iron phosphates present in the soil. As a result of this action, the very insoluble compounds, calcium aluminate * and calcium ferrate, are probably formed in some amount, with the consequent production of the more readily soluble calcium phosphate. Thus in adding phosphatic manure to calcium-deficient sour soils, lime should first be applied to precipitate aluminium and iron.

It is interesting to note in this connexion, that dicalcium silicate (Ca_2SiO_4), an artificial product obtained by leaching a mixture of natural rock silicates, has been found equally as effective as calcium carbonate in correcting soil sourness due to excessive concentration of aluminium-ion in the soil solution [24]. It has already been stated (p.176) that calcium superphosphate acts in a similar manner.

III. The Lime Requirements of Soils.

In order to obtain definite information as to the quantity of lime that might be required to bring a given soil into a more suitable condition for crop growth, soil scientists have long been striving to elaborate experimental methods for determining lime requirements of soils. Until recently it was firmly believed that the necessary condition of a soil for optimum plant growth is a condition in which the soil is fully saturated with lime. By this was really implied that a soil, in order to be highly productive, should possess a neutral or slightly alkaline reaction, acidity being thought in all cases to be detrimental to plant growth.

In order to illustrate the methods whereby soil scientists have attempted to measure the lime requirements of soils, a few typical examples will briefly be described.

1 The Tacke Method.

One of the earliest methods elaborated for estimating lime requirements is that due to Tacke† (1897). It consists essentially

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* See p. 176 Mirasol [12].

†Chem.-Zeitung, 20, 1897, p. 174

in shaking together for a specified length of time soil and finely divided calcium carbonate in weighed portions, both previously made into thin pastes with water, and allowed to react upon one another in an atmosphere of hydrogen. The liberated carbon dioxide is determined, and thus the quantity of calcium carbonate which has been decomposed by the soil acids is found. This is taken as a measure of the lime required to correct soil acidity.

2. THE VEITCH METHOD.

A much more widely used method is that due to Veitch* (1902). A solution of calcium hydroxide of known concentration is added in varying amounts to unit quantities of the soil under examination until that proportion of lime-water to soil is found where the mixture, after being boiled down to dryness and then extracted with water for twenty-four hours, gives a neutral reaction to phenolphthalein. This method, besides taking into account the lime needed to neutralize soil acidity, also allows for the lime absorbed in other processes, such as the flocculation of colloidal particles.

3. THE HUTCHINSON—McLENNAN METHOD.

This method, as described by its inventors in 1915†, differs from the last two in that a solution of calcium bicarbonate of N/50 concentration is used instead of a solution of an alkaline-earth hydroxide. In this respect it therefore more nearly represents the liming of soils, in which calcium bicarbonate, as has been shown in another place, is the active agent. The soil is shaken with the bicarbonate solution for an arbitrary length of time (three hours is specified). The amount of lime absorbed is estimated by noting the differences in the readings obtained by titrating separately a certain volume of the filtered solution, and an equal volume of the initial bicarbonate solution against N/10 acid, using methyl orange as indicator.

4. THE BOUYOUCOS METHOD.

Bouyoucos in 1916†† suggested a method which only differs essentially from the one proposed by Veitch in that the end point of the reaction between soil and lime-water is found by freezing point determinations.

5. THE ELECTROMETRIC METHOD.

Sharp and Hoaglan‡ (1916) have examined the possibility of using the hydrogen-electrode for estimating the lime requirement of soils. To the mixture of soil and water in the reaction

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Journ. Amer. Chem. Soc. 24, 1902, p. 1120. See also Watts[56] for full details and a discussion of the method.

†*Journ. Agric. Sci.*, VII, 1915, p. 75. See also Watts[56].

††Mich. Agric. Expt. Sta. *Tech. Bull.* 27, 1916. See also Watts[56] for a full discussion of the method.

‡*Journ. Agri. Res.* VII, 1916, p. 123.

vessel, a standard solution of calcium hydroxide is added, until a definite alkaline reaction is obtained corresponding to pH values above 7·0 In this way the amount of lime needed to impress any desired degree of alkalinity under the conditions of the experiment can be ascertained.

Knight* (1920) performed a similar experiment in which he recorded the change in potential of the hydrogen electrode immersed in a suspension of an acid soil on shaking the suspension with a solution of calcium hydroxide. He found in another experiment† that the addition of a neutral salt to the mixture of soil and lime greatly increased the speed of reaction between the soil acids and the base.

6. THE COLORIMETRIC SYSTEM. (See[21] p. 54.)

An attempt was made by E. A. Fisher‡ to measure lime requirement by adding varying amounts of base (barium hydroxide was chosen) to a series of mixtures of soil with twice its weight of water, shaking for an hour and then measuring the pH value colorimetrically after centrifuging. By plotting the values of interpolating at pH = 7·0 (i e neutrality), the amount of lime required to bring the reaction of the soil to neutrality under the conditions of the experiment could be calculated.

Numerous investigators‡‡ have at different times compared the above and other methods for measuring lime requirements of soils, and have found that the variations introduced in the procedure, and the difficulties experienced in the final measurement of the end-point lead to very considerable discordance in the values obtained.

It has been shown, for instance, that the degree of subdivision[13] of the soil used in the lime requirement estimation; the chemical nature and state of the base[32], [53] or the concentration of the basic solution added[13]; the length of time allowed for the interaction between soils and base[13]; the effect of shaking; the temperature [51] [53]; the presence or absence of a neutral salt[32]; and the physical type of soil examined[13], each plays a part in deciding the final result.

Possibly the chief reason for many of the inconsistencies in the recorded experimental data lies in the fact that soil acids, whatever be their nature, vary greatly in activity, and are formed continuously in the soil at rates depending upon numerous interrelated factors, such as the degree of soil aeration and soil moistness, the extent to which leaching and absorption

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Journ. Ind. Eng. Chem., XII, 1920, p. 463 [32].
†Ibid. p. 461.
‡*Journ. Agric. Sci.*, XI, 1921, p. 57 [13]
‡‡For example :—
Schollenberger. *Soil Sci.*, III, 1916, p. 279.
Christiansen. *Soil Sci.*, IV, 1917, p. 115.
Bear. *Soil Sci.* IV, 1917,, p. 433.
Stephenson (53).
Knight [illegible] (32).
Robinson [illegible] (53).
Fisher [illegible] (13).

by plants go on, and the action on the soil of added fertilizers. Thus under varying environmental conditions the complex soil components yield hydrogen-ions to the soil solution at correspondingly varying rates. The numerous actions and reactions involved, however, tend slowly toward the establishment of a condition of equilibrium. The introduction of lime into the system of soil and plant upsets this balance, and time is needed for the equilibrium condition again to become established. The fact that liming, apart from neutralizing soil acidity, also has an effect in bringing about important changes in the degree of dispersion of the colloidal particles in the soil[13], and in reacting with certain inorganic compounds, such as iron and aluminium-bearing minerals, further complicates matters, for in certain cases a considerable proportion of the added lime may be used up in these processes.

In most instances the extent of the time factor cannot easily be gauged. Experimental evidence points to its duration as being measurable only in months, or even years. It is not to be wondered, therefore, that laboratory methods for estimating the lime requirements of soils have so far proved to be of no very great practical value, or that it should seem impossible to elaborate some method which would be entirely satisfactory.

On the other hand, lime requirement methods have their uses in that they supply the investigator with some evidences as to the causes of acidity in particular soils, especially when the results obtained by their employment are considered along with other data, such as hydrogen-ion concentration of the soil solution and the degree of colloidality of the soil. Information gained from their application to soils also furnishes a basis for outlining and prosecuting field trials, and for this reason alone, lime requirement determinations will always be of some value to the agronomist.

As instances of the correlation between laboratory evidence and field practice in this connexion, the following examples may be noted.

McIntire[42] observed that when calcium carbonate is applied to soils in excess of the amount found by laboratory experiments to be necessary to bring the soil to a neutral reaction, the excess of lime gradually disappeared, demonstrating the existence of a long-continued reaction between soil and lime. Hoagland and Christie[27] record similar results.

Stewart and Wyatt[54] found that the neutralization of soil acidity, brought about by applying lime to soil plots at the Illinois Agricultural Station, was a very slow process, due in part at least to mechanical difficulties in mixing the lime into the soil, and to the coarseness of the material used. Even after three and a half years the acidity of certain soils had not been neutralized, though heavy lime dressings had been applied.

Blair and Prince[4], in their studies of the limed plots at the New Jersey Agricultural Station, attempted to correlate lime requirement, as measured by the Veitch method, with hydrogen-ion concentration of the soil extract. They found that the

decreases in lime requirement were not altogether proportional to the amounts of lime added. Some positive relationship was discovered between lime requirement and hydrogen-ion concentration, and it was found possible to assign in most cases a fairly definite lime requirement figure to a given pH value. Joffe [30], at the same station, observed that, with sandy soils low in organic matter and exhibiting little buffer action, an adjustment of reaction based on quantitative indications given by hydrogen-ion determinations may be accomplished by liming.

IS SOIL NEUTRALITY ALWAYS ESSENTIAL FOR OPTIMUM PLANT GROWTH?

Two other investigations are worthy of note in connexion with the much debated question of the relation between soil fertility and reaction. Cook and Allison[10], in pot culture experiments on the growth of buckwheat in lime acid soils of three types, found that a small application of lime produced nearly as large a crop yield on sandy loam and silt loam soils receiving ammonium sulphate as did larger amounts, and even better results in the case of sandy soils. Where large amounts of lime were applied at one application, it appeared that considerable unnecessary loss might be experienced in the cultivation of buckwheat. Buckwheat grown in the more acid soils showed a higher nitrogen content but a somewhat smaller yield of crop than buckwheat grown in neutralized or alkaline soils; the recovery of nitrogen from the acid soils was evidently as great as, or even greater than, that from neutral or alkaline soils. These results were interpreted as implying that buckwheat is able either to take up its nitrogen as ammonia (which has been shown, however, by previous nutrient culture experiments, not to be a common faculty of this plant), or else nitrification proceeds to a considerable extent in the presence of acids.

Hartwell and Pember[23] noted in field experiments conducted at the Rhode Island Station that, under conditions where liming exerted very little influence upon the growth of rye, barley was increased two to threefold. Evidently these two crops are affected differently by acid soil conditions. Investigations with nutrient water and sand cultures of rye and of barley were inaugurated in order to test this conclusion. It was found that a given amount of acidity artificially created by adding sulphuric acid to the nutrient media produced approximately equal effects on the growth of rye and barley seedlings. Hence an excessive concentration of hydrogen-ion is not the limiting factor to growth in the case of barley rooted in soils of acid reaction at the Rhode Island Station. Numerous other possible inhibiting factors were examined, and by a process of elimination, it was finally proved that an excessive concentration of aluminium-ion in the soil solution was responsible for the different influence of these acid soils on the crops mentioned. Whereas rye can withstand considerable concentration of aluminium-ion in the soil solution, barley is eminently sensitive to it. Liming therefore increases the productivity of the Rhode Island soils to barley, mainly because it precipitates active

aluminium in the soil solution. Superphosphate* was found to have similar beneficial results for the same reason, even despite the fact that its use appreciably increased the acidity of the soil growing the barley crop.

This instance has been considered in some detail because it furnishes an excellent example of the fallacy in the statement that liming in all cases is a positive remedy for that type of infertility that is usually associated with an acid soil condition. Doubtless many other examples exist amongst the commonly cultivated crops†, and detailed investigation is urgently needed in order to settle definitely, which of the factors known to be associated with an acid reaction is fundamentally responsible for the low productivity of certain sour soils growing specific crops.

The indiscriminate use of lime is to be condemned almost as strongly as a neglect to employ it in those particular cases where beneficial results can positively be expected to follow, and where economic reasons do not entirely prohibit its inclusion amongst the soil amendments regularly purchased.

The numerous data adduced in this paper and in the author's article on soil sourness[21] indicate that soil acidity, *per se*, is not always an objectionable condition which invariably requires an application of lime for its correction. In fact, soil acidity may in certain instances be beneficial in controlling plant diseases, or in preventing malnutrition. Workers in the United States have long been aware of these facts, indeed Coville[11] in a recent official bulletin has evolved a rational system of acid land farming based on the selection of acid tolerant crops to be grown in rotation, which promises great economic returns to those who are concerned in the cultivation of the vast areas of sour soil that exist in parts of the United States.

It has even been advocated that in certain specific cases, for example, the cultivation of scab-free potatoes, a definite degree

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*So too was dicalcium silicate[24].

†In particular reference to the West Indies, attention is drawn to the statements made by Watts[56] (pp. 340-1).

(a) *Cacao*. 'In the many experiments that have been made in adding lime to the soil of cacao orchards, it has seldom resulted that the crop has been markedly increased.'

(b) *Limes*. 'The evidence from Dominica and other West Indian islands shows that lime trees will flourish on soils containing remarkably small quantities of carbonate of lime.

The writer has been able to verify this latter statement by his own observations in Dominica. It would seem possible that many West Indian soils, derived from volcanic rocks and frequently exhibiting markedly acid reaction, might contain excessive concentrations of aluminium-ion in the soil solution. The fact that lime trees, and indeed most of the common West Indian crops (Watts, *loc. cit.*, p. 340) apparently thrive quite satisfactorily in such soils, would seem to indicate that these plants possess considerable tolerance to aluminium. This supposition requires to be tested experimentally, however, and there is need for detailed investigation into the degree of tolerance to aluminium and to other toxins that the various West Indian cultivated plants exhibit. This done, it would then be possible to offer more definite advice as to the desirability of liming, or at least, as to the necessity for field trials on the liming of these plants in the West Indies.

of acidity should be impressed on an otherwise neutral or alkaline soil by the use of sulphur or some other acid-yielding substance.[34] (See also[41], pp. 65 and 66.)

There is obviously much need for further investigation along the lines indicated in this article, not only in the laboratory, but also in the field, for liming must in future be looked upon as an exact operation to be performed only when accurate information regarding the significance of the various factors that might be involved in its employment has been accumulated for any particular soil, and for any particular crop.

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STUDIES IN WEST INDIAN SOILS.

II. THE SOILS OF MONTSERRAT, THEIR NATURAL HISTORY AND CHIEF PHYSICAL PROPERTIES, AND THE RELATIONSHIP OF THESE TO THE PROBLEM OF DIE-BACK OF LIME TREES.*

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INTRODUCTORY.

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(B) The Main Soil Types of Montserrat.

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INTRODUCTORY.

During April of 1921, the writer assisted in a reconnaissance, undertaken by the plant physiologist of the Imperial Department of Agriculture, of the condition of the chief lime plantations of Montserrat. In this investigation, the ecological relationship between the soil conditions and the growth of lime trees was especially considered. It became evident during the course of the work that a preliminary discussion of the main features of the soils of Montserrat might be of service in future detailed research into the already much-studied problem of the die-back of lime trees, as well as in connexion with general questions of crop growth in Montserrat. The soil work was accordingly extended to include most of the land now under cultivation in Montserrat.

There has been too great a tendency in the past to discuss the potentialities of West Indian soils in terms of their laboratory analyses alone. Little, if any, reference has been made to their geological, topographical and ecological relationship in the field. In the following article, the geology and the chief physical properties of the main soil types of Montserrat are first described. In Part II, the possible bearing of the chief physical properties and field characters of the soils of lime plantations on the problem of cause of die-back of lime trees is considered in some detail. This part of the article is intended to form a basis for future considerations of the physiological aspects of die-back. For the guidance of workers in soil problems in the West Indies, an account of the methods used in this investigation is given in Part III of this paper.

The writer wishes to acknowledge his indebtedness to W. Robson, Esq., Curator of the Montserrat Botanic Station, for help in collecting certain data connected with the Agricultural conditions in Montserrat, and to A. W. Gallway, Esq., Assistant Curator, for his kindness in obtaining many of the soil samples examined.

PART I. THE NATURAL HISTORY AND CHIEF PHYSICAL PROPERTIES OF THE SOILS OF MONTSERRAT.

(A). THE GEOLOGY AND TYPOGRAPHY OF MONTSERRAT.

Monsterrat belongs to a continuous chain of islands that constitutes the volcanic or inner zone of the Antilles [22]*. This zone extends from Saba in the north to Grenada in the south. The islands included in it are of geologically recent origin, although the majority of them possess a foundation of older volcanic rocks of probable Miocene age. [15].

The rocks of which Montserrat is composed consist almost entirely of fragmental material derived from igneous rocks of subalkaline type, chiefly hypersthene-andesite or trachyte [21, 27] This fragmental material has been ejected from sev-

*The figures in small type indicate the numbers of the references to literature cited in the appendix.

eral centres, so that several distinct volcanic cones are recognizable in the island. The chief of these comprise the South Soufrière Hill, (2,500 feet); the Soufrière Hills, (3,000 feet); the Centre Hills, (2,500 feet); St. George's Hill, (1,200 feet); and Silver Hill, (1,300 feet).†

No lava flows appear to exist in the island. Coral rock, forming recent fringing reefs, occurs in places round the coast.

Since its ejection, the fragmental volcanic material has been largely consolidated into agglomerates, breccias and tuffs, which are clearly to be seen in numerous sea-cliff sections. Where these rocks are exposed at the surface of the land, as they are especially in the northern half of the island, they are locally known as 'Shoal' rock.

Extensive erosion has gone on in the highlands of Montserrat. One result of this has been the formation of several well-marked talus slopes, composed of loose material which spreads out in fan-shapped masses from deep cirques situated near the summits of certain of the mountains, and reaches down to the coast. The most conspicuous of these talus slopes occur in the south of the island, having their origin in the Soufrière Hills. Especially noteworthy are the talus slope that abuts on the south-west coast between Plymouth and O'Gara's, and the slope which terminates in the gently inclined ground on the east (windward) side of the island between Trant's and Tar River. A third series of smaller talus slopes of some importance extends from the St. George's Hill range westward to the coast north of Plymouth.

Surface erosion has carved out of the loose material of which the talus slopes are composed, numerous narrow ravines which possess almost vertical walls. These ravines are locally known as 'ghauts' or 'guts,' and are frequently of great depth. They are usually dry except during periods of excessive rainfall. In those parts of the island where talus slopes are absent or poorly developed, river action has eroded the hillsides into deep valleys. These are especially prevalent in the hill mass known as the Centre Hills, and in the central and northern parts of the island generally. They are quite distinct from the ghauts of the talus lands.

Possibly the almost entire absence of talus slopes in the northern half of Montserrat, and the occurrence, in this region, of well developed valleys, indicate the greater age of the northern part of the island; for long-continued erosion would have the effect of removing loose debris accumulated as a result of water action of former times.

The cultivated lands of Montserrat occur chiefly on the lower parts of the hill spurs and talus slopes. They are seldom found at elevations of more than 1,500 feet. At altitudes greater than this, natural vegetation, belonging chiefly to the indigenous forest association, covers the land surface.

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†These names are taken from the Admiralty map of Montserrat, first published in 1869.

(B) The Main Soil Types of Montserrat.

The soils of Montserrat may be subdivided into two main types in accordance with their geological origin. These types may be designated—

(1) Talus soils.
(2) Shoal soils.

(1) TALUS SOILS.

Talus soils, as the name implies, are distributed over those areas where talus slopes occur. They are typical soils of transportation. The chief feature exhibited by them is their marked porosity, for they pass downwards into considerable thicknesses of loose subsoil, so that their natural under-drainage is exceptionally free. The majority of the best cotton growing estates in Montserrat are situated on talus lands, as, for example, Grove, Dagenham, and Trant's.

The cultivated talus soils of Montserrat occur chiefly at low elevations, where the rainfall is comparatively small, ranging between 40 and 60 inches per annum. Their more important physical characters may be learned by an inspection of Table I, in which the results of laboratory examination, made by the writer, of representative samples of talus soils are displayed. The data published by Watts and Tempany, who conducted a soil survey of Montserrat in 1905[27], convey further information as to the physical constitution of the talus soils, as well as to certain of their chemical properties.

The facts may be summarized as follows. The talus soils of Montserrat are light, fawn-coloured, loamy sands, notably deficient in collodial matter, and, for this reason, not very retentive of water. Their permeability is relatively very high. The soils are usually easy to till. In some localities, however, the occurrence of a high proportion of stones and small boulders interferes with tillage. On the other hand, these larger fragments lying on the surface of the land, serve in some measure to minimise loss of soil moisture by evaporation. The soils at O'Gara's, and also at certain estates situated on the large windward talus slope above Trant's (including Farm, Bethel, Tuit's and White's) are especially characterized by this feature.

Generally speaking, the lands in which loose boulders and stones preponderate, are situated on the higher or more inland parts of the talus slopes. This is a natural result of the action of mountain torrents, which are the agent that has given rise to these slopes.

The addition of bulky organic manures is the only practical means whereby the water-retaining capacity of the sandy talus soils can be increased. Soil moisture may be conserved in the drier months of the year by maintaining a loose soil mulch (see[20], [28]). This practice should receive more attention in Montserrat.

Chemically, the talus soils are highly fertile[27]. The soil reaction is distinctly alkaline, in spite of the fact that the soils contain only small amounts of carbonate. In the light of modern knowledge as to the significance of soil reaction[11], there would appear, however, to be no necessity for liming.

(2) SHOAL SOIL.

Soils of the second main type cover those areas of Montserrat where talus slopes are absent. They constitute the major part of the uncultivated land of the island, as well as land that is unsuited to the growing of the best cotton. Shoal soils are typical sedentary soils, for they have been derived from consolidated fragmental rocks which they usually directly overlie. For this latter reason, natural under-drainage is at a minimum; a fact which distinguishes the soils markedly from those of the talus slopes.

Shoal soils are typically developed in the northern half of Montserrat; they also occur in the extreme south-eastern part of the island in the South Soufrière district.

Consequent on differences in the amount of rainfall (which are the result of varying altitude), in the degree of land slope, and in the presence or absence of a natural covering of vegetation, three distinct sub-types of shoal soils may be defined. For convenience of description, these may be designated :—

(a) Humid upland Soils.
(b) Hilly land Soils.
(c) Valley Soils.

The sub-types named in this list merge imperceptibly one into the other. The factors that have been responsible for their differentiation are mainly climatic and topographical in nature, as is indicated by the names chosen for the sub-types.

(a) *Humid upland Soils.* Soils of this sub-type occur in Montserrat at elevations of 1,000 feet and over. The annual rainfall in these regions varies between 60 and 100 or more inches. The greater part of the Montserrat uplands lying above the 1,000 feet contour is still clothed with virgin forest of floristic composition, very similar to that comprising the dense forests which almost entirely cover the humid mountainous islands of the Lesser Antilles (Dominica, Martinique, St. Lucia, etc.), and which occupy the more elevated regions of the majority of the other islands of the group.

The soil conditions in the uplands of Dominica, where the annual rainfall varies between 150 to 300 inches, have been discussed by the writer in a recent paper[2]. The main features of the upland forest soils of Dominica are exhibited in modified form by the upland soils of Montserrat.

The chief physical characteristics of the Montserrat upland soils are set out in Table II. Sample 5 was taken at an altitude of about 1,300 feet, from forest land where cacao and lime trees have been planted. It is typical of the unreclaimed forest soils of Montserrat. The soil is markedly acid in reaction (pH 6·7). It is not so acidic, however, as the Dominican upland soils, whose reactions vary between pH 4·4 and 5·1 ([1], p. 101). This fact may be interpreted as indicating that leaching has not gone on so extensively in the Montserrat uplands as it has in those of Dominica, and is doubtless accounted for by the lower rainfall of the former region.

As may be inferred, the Montserrat upland soils exhibit incipient lateritzation ([11], p. 47 ; [12], p. 97). The soils when dry are of a reddish or yellowish colour, showing the presence of an excess of iron oxide. They are distinctly colloidal in type, and for this reason, possess high water-holding capacities and low permeabilities. Their subsoils are clayey, and of varying depth.

At Farrell's and Harris's on the broad divide that separates the Centre Hills from the Soufrière Hills, at an elevation of some 1,000 to 1,100 feet, the upland soils have been reclaimed for cultivation. They have, for a considerable period of time, been given over to the cultivation of sugar-cane. These areas are unsuited to the growth of the cotton crop, for, besides possessing a heavy type of soil, the situations are exposed to wind, and the rainfall is excessively high.

At Tar River estate, the upland soil is a yellowish brown clay-loam of considerable depth. It has been reclaimed by the recent deforestation of certain of the western spurs and valleys of the Soufrière Hills.

At Roache's occurs the most productive upland soil in Montserrat. It is a deep, brown-coloured loam, rich in humus. It supports good crops of sugar-cane.

(b) *Hilly land Soils.* In marked contrast to the talus soils and to the upland forest soils, there exist in Montserrat considerable areas of land of a generally infertile nature. Such areas are typically represented in the Silver Hill region at the northern extremity of the island and occur below the 1,000 feet contour. Here the land surface is broken up into steep hills and deep valleys. The rainfall is comparatively small, being below 40 inches per annum in some localities.

The hillslopes are exposed to wind, and in the drier months of the year are parched and bare. The soil is shallow and is underlain by consolidated volcanic ejectmenta or 'shoal.' In consequence, drainage is entirely superficial, so that in rainy weather, water quickly runs away.

The texture of these hill-slope soils is mainly sandy. Sample No. 3, Table III (Cavalla Hill) is typical of them. This soil is of low retentivity, and most of the colloidal matter has been washed out of it. It can support crops only in the wetter months of the year, and is best suited to the growth of ground provisions, whose vegetative periods are of short duration. The soil is too shallow and too subjected to water-logging in rainy weather to yield satisfactory crops of cotton.

A certain number of successful cotton estates are situated, however, on the hilly shoal lands in the northern part of Montserrat. These estates occur in localities where the topography of the ground offers some shelter from wind, and where the soil is of somewhat above the average depth. Many of the steeper hillsides in the extreme north and north-eastern regions of the island are cultivated by peasants. The soil occurs in pockets between exposed rocks, but nevertheless it can be made to produce fair crops of cotton, in spite of the difficult nature of the ground, and the general dry conditions that prevail.

Table III presents data obtained by an examination of soil samples taken from a number of hilly land estates lying between Silver Hill and the Centre Hills. An inspection of these data indicates that the soils vary in type between sandy loams and clay loams. They are pale reddish-brown in colour when dry, and slightly acid, neutral or distinctly alkaline in reacion. A red clay subsoil underlies the soils. This passes rapidly in most places into the shoal rock at no great depth.

The lower and less steep of the hills in the northern part of Montserrat have not been subjected to denundation to the same extent as have those of the more elevated regions of the island such as are unprotected by forest growth. This is especially noticeable in the hills that fall in gentle undulations to the seacoast in the north-west part of the island. Here the comminuted products of rock weathering have remained *in situ*, or have collected in the hollow places. The soil produced from this debris is markedly clayey, and is frequently of considerable depth. Such clay soil is typically developed at Olveston (see [27], p. 280) where its untractable nature caused the abandonment in 1910 of the Experiment Station that formerly existed there.* The clay soils of the foot hills are unsuited to the growth of the majority of crops, excepting certain grouud provisions.

A characteristic natural plant association occurs on the slopes of the low hills of the north-west coastal region. The dominant species of this association are thorny xerophytic shrubs, such as various 'cossies' (*Acacia farnesiana*, etc.); Sages (*Lantana* spp., and *Cordia cylindristachya*,) and the common croton (*Croton flavens.*) This plant association is represented in many West Indian islands, and invariably occurs on shallow, badly-drained pockety soil that covers dry, wind-swept hills near the seacoast. It has been named by Egger the *Crotoneta* association. [6]

(c) *Valley Soils.* In the valleys of the northern part of Montserrat, considerable thicknessess of weathered rock debris have collected, and have given rise to a third type of shoal soil. By reason of the shelter from wind afforded by these valleys, and the general humid conditions of air and soil, occasioned by the permanent presence of streams in them, the northern valley soils are of considerable fertility. They support a prolific natural vegetation of an arboraceous type, especially in their lower reaches. In places, they have been planted with lime trees, as for example, at Old Road, Ile's Bay and Elberton. Many fruit orchards have been established in them. The uniformity of these valley soils is broken by the presence of boulders, except in those regions near the coast where the valley floors widen into small alluvial flats. The soils are sandy loams

*Report of the Montserrat Botanic Station, 1909--10, p. 20.

or clay loams, similar in physical properties to certain of the hilly-land soils last described. They differ from these, however, in that their under-drainage is good, and in that they are not subjected to drought. Sample 3, Table IV, is typical of the soils of the smaller of the northern valley bottoms.

In the central part of Montserrat, a wide and large valley separates St. George's Hill from the Centre Hills. The river

which it contains (Belham River) has its origin in the Soufrière Hills, whence it flows in a north-westerly direction to the sea at Old Road Bay. The gently sloping sides of this valley include large areas of productive land as, for example, the lower parts of Lee's-Week's and Waterworks Estates. The chief crops grown are sugar-cane and cotton.

The soil in this region has been derived in part from talus slope material to the south, and in part from the weathered shoal rock to the north. It is therefore a typical transition soil. In physical character, it is a deep silty loam grading into a sandy loam when traced northwards. Unfortunately, no samples of these transition valley soils were examined in detail by the writer, but a study of the data presented by Watts and Tempany ([27], pp. 267 and 278) will indicate their general features and relationships.

TABLE I. : (1) *Talus Soils.*

Soil Number.	Name of Locality.	Height above sea-level (feet).	Rain fall (inches per annum).	Physical soil type.	Colloidal matter (per cent.).	Max. water-holding capacity (per cent.).	Permeability to water (Pw X 100).	Reaction pH value.
11.	Trant's.	20	43	Medium sandy.	10·6	29·8	15·4	7·3
2.	Grove (Upper)	250	58	Loamy sand.	14·4	39·2	7·8	7·2
1.	Grove (Bot. Sta.)	150	60	Loamy sand.	15·3	44·5	15·0	7·3
16.	O'Gara's (Lower)	50	43	Loamy sand.	16·1	50·6	20·7	7·3

The following soils belonging to this type were examined by Watts and Tempany [27]: Trant's, Grove, Gagé's, Bethel and White's.

TABLE II : (2) *Shoal Soils.*

Sub-type (a), Humid Upland Soils.

5.	Centre Hills	1,300	100	Clay soil.	40·4	62·4	1·1	6·7
17.	Roache's (Upper)	1,400	90	Sandy loam.	27·2	55·3	8·9	7·2
20.	Tar River (Upper)	1,000	80	Clay loam	32·7	50·4	7 0	6 9
12.	Farrell's	1,100	80	Clay loam.	30·6	50·2	5·6	6 7
13.	Harris's	1,000	60	Sandy loam.	26·3	48·7	4·2	7·0

Examined by the Watts and Tempany [27]: Tar River, Farrell's, Harris's.

TABLE III : (2) *Shoal Soils (Cont'd.).*

Sub-type (b), Hilly Land Soils.

8	Cavalla Hill	500	60	Sandy loam.	29·0	42 6	3 2	6 9
10	Blakes	600	55	Sandy loam.	29 3	40·2	6·7	6·8
19	Rendez-vous	200	40	Sandy loam.	28·4	44·1	3·9	7·1
9	Gerald's	400	45	Sandy loam.	27·6	44·3	2 9	6 9
14	Barzey	860	53	Sandy loam	26·3	51·1	7·0	6·7
6	Braid's	300	50	Clay loam	31·4	53·t	5.0	7·6
7	Sween-ey's	500	50	Clay loam.	39 8	63·2	5·4	7·4
4	Olveston (foot hills)	300	60	Clay loam.	37·4	60·1	4·4	6 7

Examined by Watts and Tempany [27] : Olveston.

TABLE IV : (2) *Shoal Soils (Concl'd.).*

Sub type (c), Valley Soils.

3.	Olveston Valley,	20	55	Clay loam.	33·1	51·9	6·4	7·1

Examined by Watts and Tempany [27] : Ile's Bay, Lee's, Weeks's.

(C) THE CLIMATIC CONDITIONS IN MONTSERRAT.

It would be convenient for purposes of reference to summarize in this place the data obtained by meteorological observations systematically carried out at several stations in Montserrat, and recorded in the annual reports of the Botanic Station.

(1) *Rainfall.* The following table (Table V) contains the names of stations for which rainfall data are available over periods of not less than five years The stations are arranged in the order of magnitude of their average annual rainfall. The approximate altitude and the geographical position of each station are also stated.

TABLE V. Average annual rainfall returns, Montserrat.

Name of Station.	Average annual rainfall (inches)	Number of years (average).	Approx. altitude (feet).	Geographical position.
Riley's ..	78·2	5	1,000	Leeward slope; central divide.
Woodlands ..	65 9	12	900	Leeward coastal belt; north.
Amersham ...	61·0	6	500	Leeward coastal belt; south.
Waterworks	32·4	6	600	Leeward slope, Centre Hills.
Grove ..	60·5	12	150	Leeward coastal belt; centre.
Olveston ...	60·0	12	600	Leeward coastal belt; centre.
Harris's ...	59·5	12	800	Central divide; highest land.
Richmond ...	58·4	12	200	Leeward coastal belt; centre.
Dagenham ...	53 0	12	150	Leeward coastal belt; centre.
Ile's Bay ...	51·4	12	50	Leeward coastal belt; centre.
Kinsale ...	50·5	12	50	Leeward coastal belt; centre.
Blake's ..	47·5	7	600	Windward slope; northern hills.
Elberton ..	46·8	12	50	Leeward coastal belt; centre.
White's ..	43 7	12	600	Windward coastal belt; centre.
O'Gara s ..	43·5	12	50	Leeward coastal belt; south.
Roaches lowlands ..	43·3	7	500	Windward coastal belt; south.
Trant's ...	40·8	12	50	Windward coastal belt; centre.
Bethel ...	39·3	12	200	Windward coastal belt; centre.
Farm ...	33 5	12	150	Windward coastal belt; centre.

Neglecting the upland regions of elevation of 1,000 feet and over, it is seen from the data presented in Table V, that the magnitude of the rainfall in the different parts of Montserrat is not very great, nor is it very widely divergent. The leeward side of the island, on the average, receives more rain than the windward side. This is directly opposite to the rainfall distribution in the more mountainous of the West Indian islands, as for example, Dominica. In Dominica, the leeward coastal belt is much drier than the windward coastal belt. This difference is so marked that it has made a profound impress on the character of the soils of the two regions (see [12], pp. 94-106). No such differentiation of soil types correlated with geographical position can be definitely traced in Montserrat. On the whole, the districts of highest rainfall in Monsterrat appear to lie on the leeward (western) slopes of the Centre Hills and the Soufrière Hills. Within this region, the more elevated districts receive the greater rainfall. The driest parts of the island occur in the extreme north and south-west, and along the windward coastal belt.

Records indicate that the mean annual rainfall of Montserrat during the past thirty years has exhibited a fairly well-marked periodicity. This is clearly shown by the figures in Table VI, which have been abstracted from the data presented at

page 40 of the annual report of the Montserrat Botanic Station for 1919-20. The average annual rainfall for the island, as indicated by the returns of numerous (6 to 22) stations during the past thirty years, is 57 inches. It has fallen below this in fairly regular four-year periods, and has risen above it in alternate periods, of the same duration. The reason for these facts are obscure. Contrary to repeated assertions, it appears that the average annual rainfall of Montserrat has not decreased abnormally during the past thirty years. This conclusion has some significance in connexion with the question of die-back of lime trees*

TABLE VI. Periodicity in the average annual rain fall of Montserrat during the past thirty years.

Years of low rainfall.			Years of high rainfall.		
Year.	Approximate annual average rainfall	Difference from the thirty years mean of 57 ins.	Year.	Approximate annual average rainfall.	Difference from the thirty years mean of 57 ins.
1894	47	-10	1896	93	+36
1900	43	-14	1901	65	+ 8
1904	48	- 9	1906	67	+10
1907	47	-10	1909	66	+ 9
1912	42	-15	1913	56	-
1914	46	-11	1916	68	+11
1918	46	-11	-	-	-

The rainiest months of the year in Montserrat are usually September, October and November. The months December to June are generally comparatively dry, so that there is some indication of alternating wet and dry seasons in the climate of Montserrat. This alternation is not, however, always very clearly marked; the rainfall may be relatively large during any period of the year.

(2) *Prevailing Winds.* Montserrat is windswept for the greater part of the year. During the drier months, the north-east trade wind blows with great persistence, and frequently with violence. The exposure to wind of lime trees growing in open fields is a factor which has been considered of major importance in the relation to the growth

*Annual Report of the Montserrat Botanic Station, 1917-18, p. 13.

of limes in Montserrat†. Attempts to minimize its effect by the planting of wind-breaks have received increasing attention from lime growers in recent years*.

Some idea of the velocity and regularity of the wind in Montserrat may be learned from the observations which have been recorded at the Botanic Station since 1915*. The average wind velocity, measured in miles per hour, is 8 3. It is greatest, in general, during the months of January to August.

(3) *Atmospheric temperature and humidity.* Records of atmospheric temperature at the Grove Botanic Station have been kept since June 1913 The mean maximum temperature for the seven-year period, 1913-19, is 86·6°F, and the mean minimum, 73·4°F.

The mean relative humidity of the atmosphere at the Botanic Station over the five-year period 1915-19 is 70·9 at 9 a.m., and 65·1 at 3 p.m.

Unfortunately, no meteorological records are available for other localities in the island nor are any similar data available for Dominica. One cannot therefore draw exact comparisons between the atmospheric conditions of the two somewhat contrasted regions in which the lime tree is grown.

PART II. THE RELATIONSHIP BETWEEN CERTAIN SOIL FACTORS AND DIE-BACK OF LIME TREES.

(A) The Problem of Dieback of Lime Trees in Montserrat.

The cultivation of the lime tree in Montserrat has been attended from the date of its inauguration in 1852 with many difficulties. Especially since the disastrous hurricane of 1899, has the condition of the lime orchards been steadily deteriorating. The records published in the annual reports of the Montserrat Botanic Station subsequent to 1906 contain repeated reference to this unsatisfactory state of the lime industry.

The decline of the lime trees has taken the form of a gradual cessation of growth, accompanied by a dying back of branches and frequently also, a yellowing or mottling of foliage. An almost invariable symptom of die-back, concomitant with those above-mentioned is the marked prevalence of scale insects on the branches and leaves of affected trees. Occasionally the roots show damage due to attacks of soil grubs, and, finally, infestation of twigs and roots by certain fungi has been noted

The constant association of scale insects with the die-back condition led to the original belief that the two were causally connected. Hence the early attempts to combat die-back of lime trees consisted of various cultural treatments of the soil, and of spraying trials with different insecticides, the immediate object of which was the suppression of scale. Efforts to encourage the spread of entomogenous fungi and of certain predaceous enemies

† Ibid, 1915-16, p. 11.
* Ibid, 1918-19, p. 17; 1919-20, p. 27.
* Ibid. 1915 to 1919.

of scale insects by sheltering the lime trees with screens of shrubs or covers of creeping plants, were also made at various times. The result of these experiments are fully described in the annual reports of the Montserrat Botanic Station published during the past twelve years. On the whole, the experiments were not very successful.

During recent years there has been an increasing tendency to consider scale insects and fungi as facultative rather than causative parasites of lime trees in Montserrat, and to lay most stress on the direct effects of an unfavourable environment, as the major factor responsible for die-back* The accumulated evidence, as far as it is susceptible of interpretation, points especially to unsatisfactory water relations between the lime trees and their environment as the most likely reason for the persistent failure of the trees, not only in the older plantations, but also in those that have been but recently laid down.

In the absence of records of actual numerical measurements of the factors that affect the water relations between the lime plant and its environment, no definite conclusions, however, can be drawn from the scanty data available.

It was with a view to obtaining further insight into the ecological conditions under which lime trees are growing in Montserrat that the plant physiologist of the Imperial Department (T.G. Mason) and the writer visited the island in April 1921. During this reconnaissance, the writer's especial concern was with the soil conditions of the lime plantations, considered in their broadest aspect. The results of this investigation are set out in the following paragraphs. The physiological phases of the die back problem will receive detailed consideration in a seperate paper, by Mason. It is hoped that these contributions to our knowledge of the causes of die-back of lime trees, will lead to greater definition of the problem of its elimination, and to the formulation of more successful methods of lime orchard cultivation. It is not to be expected that conclusive evidence can be collected by making a limited number of observations during a short visit covering only a very small fraction of the total vegetative period of the plant species under consideration. Nevertheless, a preliminary investigation of an ecological problem frequently suggests the form which future detailed work should take, and fixes the attention of officers concerned in the routine study of a particular crop on the salient facts about which further information is desired.

(B) Soil Conditions in Relation to Die-back.

The preliminary soil iuvestigation now to be described consisted in the collection and examination of representative samples of the soil of certain lime plantations, with a view to detecting variations that might in part be correlated with the incidence of die-back. Samples were taken of soil in which were rooted (A) lime trees exhibiting die-back, (B) healthy lime trees

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*Annual Report of the Montserrat Botanic Station, 1915-16, Mycologist's Report, pp. 9-12.

Each sample was composed of mixed surface soil obtained from the root region of ten trees of the same age and general condition. Soil samples A and B were produced from each of three districts in Montserrat at present in lime cultivation. The names of these districts are (1) Grove, (2) Olveston, (3) O'Gara's. They are typical of the lime-growing areas belonging to the Montserrat Company.

For purposes of comparison, soil samples 4 A and 4 B were obtained in Dominica. The first of these was taken from Saltoun Estate, in the rainy upland region of the interior of the island. The second was taken from the mulched plot of the Roseau Lime Experiment Station.

Finally, soil samples 5 A and 5 B were obtained in Antigua at Dimsdale Estate situated in the south-east of the transition region of the volcanic area, (see [27]; soil number 43, pp. 96-97). Dimsdale is the only locality in Antigua where limes are grown as an orchard crop[25].

The accompanying table (Table VII) presents the data obtained in an examination of the soil samples enumerated.

Table VII.

RESULTS OF AN EXAMINATION OF SOIL SAMPLES OBTAINED IN CONNEXION WITH A PRELIMINARY INVESTIGATION INTO DIE-BACK OF LIMES.

Soil number, and state of trees.	Name of locality.	Rainfall (inches per annum).	Physical soil type.	Maximum water-holding capacity.	Permeability to water (Pw × 100).	Reaction Ph value.	Organic matter (per cent.).	Soluble humus (per cent.).
	Montserrat.							
1 A*	Grove, (Belle field)	58	Loamy sand	39·2	7·8	7·2	1·84	0·68
1 B†	Grove, (Bot. Sta.)	60	Loamy sand	44·5	15·0	7·3	2·15	0·70
2 A	Olveston, hilly land	60	Clay loam	60·1	4·4	6·7	5·15	1·05
2 B	Olveston, valley	55	Clay loam	51·9	6.4	7·1	4·27	0·73
3 A	O'Gara's, coastal land	43	Loamy sand	50·6	10·7	7·3	2·41	0·56
3 B	O'Gara's, hill.	45	Sandy loam, very stony	44·4	7·4	7·5	3·03	0·89
	Dominica.							
4 A	Saltoun, 9-acre plot	200	Humus silty soil	100·0	9·5	4·7	16·87	6·40
4 B	Mulched plot, lime expt. sta.	80	Sandy loam	44·3	4·1	6·8	2·96	1·17
	Antigua.							
5 A	Dimsdale, Nora field	40	Fine silty soil	59·5	0·5	7·5	2·34	0·51
5 B	Dimsdale, valley.	40	Fine silty soil	49·3	1·9	7·5	2·36	0·50

*Soil samples A represent soils supporting trees that exhibit die-back.
†Samples B represent those supporting normal trees.

NOTES ON THE ENVIRONMENTAL CONDITIONS DURING APRIL 1921 AT THE LOCALITIES AT WHICH SOIL SAMPLES WERE TAKEN.

MONTSERRAT.

1 A. *Grove Estate*: Lime trees exhibiting die-back.

The Grove Estate soil sample was taken from the lime plantation known as Belle field. It was here that certain cultural and spraying experiments, designed with a view to suppressing attacks of scale insects, were inaugurated in 1915* The soil is of the talus slope type, free from large stones, and in good tilth. It was over-run with creeping weeds, chiefly *Commelina nudiflora* and *Momordica charantia.* The situation is exposed to winds, and the existing artificial wind-belts appear to be inadequate.

1 B. *Grove Botanic Station*:-Lime trees free from die back.

The soil of the small lime plot at the Botanic Station is of similar type to the last. It is very uniform in texture, deep and uncompacted. A heavy mulch of cane grass, cut from a neighbouring plot, covered the soil surface. In consequence of this, and partly also because of the sheltered position of the lime plot, the soil at the time of sampling was moist to the touch. At the lower end of the plot, the soil is deepest and moistest. The whole lime plot was free from weeds. Well-grown specimens of the leguminous shrub, *Gliricidia maculata*, occurred between the lime trees. These had been planted in pursuance of a practice first advocated in 1914. †

2 A. *Olveston* :—Lime trees exhibiting die-back.

This locality is situated on the gently sloping side of an exposed low hill near the seacoast. The soil is of the hilly-land shoal type, and supports the *Crotoneta* plant association, described in another place. It is very shallow and rocky. The lime trees have been planted chiefly in pockets of soil. At the time of sampling, the soil was very dry and compact.

2 B. *Olveston valley* :—Lime trees free from die-back.

The soil in this small valley near the sea is typical of the valley soils of the northern part of Montserrat. It is rocky but deep, especially in the pockets between boulders. The situation is sheltered, and the soil, at the time of sampling, was moist to the touch. The weeds growing between the lime trees were tall and vigorous They consisted chiefly of species belonging to the Gramineae, Leguminoseae, Malvaceae and Acanthaceae. *Commelina nudiflora* and a species of broad-fronded fern were abundant. The plant-assemblage was similar to that occurring in many humid regions of the West Indies, and resembles the flora of the bases of gullies in Barbados.

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* Annual Reports of the Montserrat Botanic Station, 1915-16 to 1918-19 inclusive. Also *West Indian Bulletin*, XI, 1911, p. 39.

† Ibid. 1914-15, p.8.

3 A. *O'Gara's, coastal region*:—Lime trees exhibiting die-back.

This locality is situated on low ground near the extremity of a steep talus slope The soil, however, is not typical of the talus soils of other districts. It is somewhat shallow and stony, with pockets between rocks. It was dry and compacted, and its weed flora was withered. Under-drainage appears not to be good, for the presence of nut grass (*Cyperus rotundus*) and *Commelina nudiflora*, growing amongst the xerophytic short-lived annuals that make up the natural plant association indicates that the land is subjected to perodic water-logging.

3 B. *O'Gara's, hillslope*:—Lime trees free from die-back.

The steep talus slope above O'Gara's is dissected longitudinally by deep ghauts, bordered by steep round-backed ridges. In the ghauts a certain amount of shelter from winds is experienced, but the slopes of the divides are exposed and dry. The lime plot examined occurs in one of these sheltered ghauts, at an elevation of some 250 feet. The soil is a brown deep loam, and is characterized by the presence over its surface of a very well-marked layer of volcanic cinders and small stones. These make up over 50 per cent of the bulk of the top soil, and their size varies between 3·0 and 0·5 cm. They form a loose stone-mulch on the soil, and, when removed, expose a plexus of lime rootlets which ramify through the moist soil. No distinctive natural plant association occurs here, but sporadic clumps of a tall grass (*Paspalum* sp.), and a yellow-flowered cactus (*Opuntia* sp.) are conspicuous amongst the lime trees.

DOMINICA.

4 A. *Saltoun, 9-acre plot*:—Lime trees exhibiting die-back.

The general conditions that prevail in the humid upland regions of Dominica, where Saltoun is located, have been briefly described in the writer's paper on the soils of that island, ([12], pp. 101, 104, 116.). The soil at Saltoun is shallow, and overlies sheet rock. The subsoil is a yellow clay. The drainage is mainly superficial, the land sloping in the direction of a natural watercourse. As a result of very high rainfall, the soil has been subjected to leaching and washing. It is markedly acidic in reaction, and it is almost continuously water-logged. The area is overrun with rank weeds, of which the panache grass (*Andropogon* sp.) supposed to indicate poor soil, is especially noticeable. The soil itself contains a high percentage of organic matter, and, for this reason, possesses a high water-holding capacity.

4 B. *Roseau Lime Experiment Station*:—Lime trees completely free from die-back.

The conditions obtaining in the sheltered valley on the southern slope of Morne Bruce where the lime plots are situated, have been described at pages 102 and 112 of the article on the Soils of Dominoia already cited. The mulched plot (13 e), which supports a vigorous and healthy crop of lime trees, is well drained, and is composed of soil in good tilth and of considerable depth. It is adequately sheltered from winds by the proximity

of lime trees of neighbouring plots, and by a dense artificial wind-belt that lines the nearest hill crest.

ANTIGUA.

5 A. *Dimsdale, Nora field* :—Lime trees exhibiting die-back.

The field is situated on gently sloping ground overlooking Falmouth Harbour, and is somewhat exposed to wind. The soil is very uniformly fine-grained, containing about 50 per cent. of fine silt, and a negligible amount of clay. In consequence it packs tightly when wetted, a result which is clearly indicated by the remarkably low permeability constant which the soil possesses. At the time of sampling (April 21, 1921), the ground was hard, dry, and much compacted. The soil is of considerable depth, but is somewhat lacking in organic matter. It is kept clean weeded, but no regular loose soil-mulch was observed.

5 B. *Dimsdale, sheltered low ground* :—Lime trees less affected by die-back.

The locality from which this soil sample was obtained, lie about ½-mile to the south of that from which the last sample was taken. A small watercourse runs through the area. The soil is coaser in texture than the last, but at the time of sampling, it was compacted and somewhat dry. The cultural treatment given to the soil is similar to that described in the last paragraph.

DISCUSSION OF THE DATA.

An examination of the figures in Table VII indicates no regular and marked differences in the values obtained for the several physical soil constants that have been determined on samples constituting each pair of representative soils. With the exception of 4 A and 4 B, the soils supporting healthy and die-back trees are texturally similar. Their water-holding capacities, and hence their content of collodial matter, are not markedly different. There permeability constants, however, vary somewhat, but never in the same direction.

The condition of the soils, as indicated by the reaction, is, in all cases except 4 A, satisfactory. None of the soils, with the exception stated, possess soil solutions in which the concentration of hydrogen-ion is sufficiently high to cause one to suspect the presence of certain inhibiting factors which might be correlated with unsatisfactory plant growth. All the soils contain medium to large quantities of organic matter, and of soluble humus.

The humus content of soils supporting citrus trees has been shown to be a controlling factor in certain districts of California There Briggs and his collaborators of the United States Bureau of Plant Industry found a mottling of the leaves of orange trees to be definitely correlated with a low content of soluble humus in the soil, and that mottling decreased as humus content increased. This discovery led to the adoption of the mulched-basin system of citrus culture, an innovation which has been followed by

a marked improvement in the condition and productivity of the citrus groves. ([4], [5]). The relation between humus content and and yield of orange trees has been further studied by Jensen, ([16]), who concluded that the active component of vegetable mulch appears to be the degradation products of freshly decomposing organic substances, rather than the soluble humus formed therefrom. There seems to be no specific advantage in using a leguminous plant rather than a non-leguminous plant as mulching material in citrus groves.

These conclusions are very suggestive, in view of the recent work in England sf Bottonley ([2], [3]), who maintains that decomposing vegetable matter gives rise in the soil to small quantities of certain complex compounds (auximones) which play a rôle in plant nutrition very similar to that of vitamines in animal metabolism.*

That the organic carbonaceous component of the soil is particularly important in the growth of citrus trees in the West Indies, is demonstrated by the results of manurial experiments now being conducted by Jones in Domincia†

Here it is found that a thick layer of vegetable mulch encourages the formation by the lime trees of numerous surface roots, which is accompanied by an increase in the productivity of the trees. The sesult may perhaps partly be explained in terms of the physical benefits which organic matter confers on the soil, especially those that are correlated with water supply. Possibility also, it may in part be due to the specific nutritional properties which humus appears to possess.

Returning to a consideration of the results of the soil investigation described in this article, it would appear from the figures contained in Table VII, that the soluble humus in the soil is not the main factor responsible for the die-back condition in the lime-growing districts of Montserrat, Dominica and Antigua. Briggs and his collaborators found that healthy citrus trees flourished on substrata in which the content of soluble humus was in exeess of 0·2 per cent. [4]. This lower limit is not reached in any of the West Indian lime orchard soils examined by the writer (Table VII).

The total amount of organic matter in the West Indian citrus soils, however, is very variable, and with the exception of the districts where soil samples 1 B, 4 A, and 4 B were obtained, the organic matter does not occur specifically as a definite surface mulch that night exercise control over the water relations between the lime trees and their sub-aerial environment. The special question of the value of heavy mulch dressings in citrus orchards in the West Indies is well worthy of continued intensive study.

There are numerous soil factors other than those so far considered in connexion with the die-back of lime trees in the We t Indies, that might have bearing on the causes of this condition. For example, Essig maintains that a certain

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* See *Agric. News*, XIX, 480, p. 295; Sept. 18, 1920.

† Annual Reports of the Dominica Botanic Station, 1912 to 1920.

die-back condition of citrus trees studied by him is produced by an irregular or improper food-supply. An excess of ammonium compounds in the soil is given as one unfavourable soil condition which may cause die-back. An irregular water-supply is also stated by Essig to lead to die-back in certain types of Californian soils that receive insufficient amounts of nitrogenous fertilizer

Lipman[18] claims, a poor nitrifying power in a soil which exhibits normal ammonifying power, may also cause die-back of citrus trees. In such a soil, the trees do not obtain a sufficient supply of nitrates, and are forced to assimilate ammonium compounds. Furthermore, when a soil's power to fix ammonium compounds is very feeble, owing to the presence of a large excess of base, a poor nitrifying power, and a strong ammonifying power may lead to nitrogen starvation of citrus trees rooted in that soil. This conclusion is in some accord with the writer's own observations on the relationship between reaction and fertility in certain lime plantations of Dominica, where it was found that those soils which possessed a limited, yet sufficient, supply of easily available base, supported, in general, the most productive crops of lime trees (12, p. 116).

Finally, Kellerman and Wright[17] noted that applications of excessive amounts of nitrogenous fertilizers frequently lead to deterioration in citrus groves. An excess of calcium carbonate in the soil was found to hasten this deterioration, in that it induced a too rapid production of soil nitrates.

In British Guiana, it has been shown by Harrison, Stockdale and Ward[13] that, during the dry season, there is an almost complete absence of ammonium compounds and a relatively large excess of nitrates in the soil. With the saturation of the soil by rains, however, the condition is reversed, and much of the nitrate nitrogen is reconverted into ammoniacal nitrogen. Possibly this sequence of events obtains in the soils of other West Indian regions where dry and wet seasons alternate.

The relationship between die-back of lime trees and the transformation of nitrogen compounds in the soil has not yet been investigated in detail in West Indian lime plantations.

It is evident, however, from the foregoing discussion that the question of nitrogen supply is intimately bound up with that of water-supply, for variations in the water-supplying power of the soil of citrus groves is apparently accompanied by corresponding variations in the rate at which suitable nitrogenous compounds are rendered available to the citrus trees. Hence it is apparent that a detailed study of the water-supply of lime plantation soils should form a necessary prerequisite to a detailed study of the more specific questions connected with the nutrition of citrus trees.

It has already been stated that the data set out in Table VII, *considered without reference to the general condition of the sub-aerial and the atmospheric environment* in those lime-growing districts examined in the preliminary reconnaissance described in this article, do not indicate the operation of any distinctive factors that might be correlated with die-back.

A consideration of the more general aspects of the environment of healthy lime trees exhibiting die back, points, however, to certain features that might be of major importance in their relation to the die-back condition. Thus it may be noted that in those districts where lime trees are making satisfactory progress, the situations are sheltered from wind, and, in general, are such that extreme variations in atmospheric humidity and amount of soil moisture are at a minimum. In each case, the geological and topographical relationship of the soils supporting healthy lime trees, tends to bring about an equalization in the rates at which the soil can supply water to the tree roots during extreme periods of drought and of rainy weather. Whereas lime trees growing on shallow, badly drained soils usually exhibit die-back, those that are rooted in deep well-drained and surface-mulched soil are less affected by the die-back condition.

Further detailed investigation, conceived with a view to giving actual numerical expression to the variations that occur throughout the year in the atmospheric humidity and in the water-supplying power of the soil of lime plantations is needed before the full importance of the water relations between the lime tree and its environment can be finally established. Such an investigation is practicably possible, and methods are available whereby the necessary measurements can be made. That variations in the water relation of the lime tree have had their effect in impressing certain morphological features on the lime itself, will be shown in the paper to be presented by Mr. T. G. Mason.

PART III.

METHODS USED IN THE SOIL INVESTIGATION.

1. *Preparation of the soil sample.*

The samples were taken with a trowel to a depth of 1 foot. No subsoil samples were obtained. The samples were sent to the laboratory and air-dried. They were then rubbed in a mortar with a wooden pestle and sifted through a 2 mm. sieve. The proportion of gravel and stones was noted. The sifted soils were used in all the experiments described below, excepting No. 6.

2. *Colloidal matter* (approximate).

This was estimated by measuring the linear shrinkage of bricks of dimensions $3 \times 1 \times 1$ inches, exactly as described by Auchinleck[1] and by Tompany[2] The percentage colloidal matter was calculated from the percentage linear shrinkage by multiplying by Tempany's factor, 4·25.

3. *Maximum water-holding capacity.*

The maximum water-holding capacity of a soil is defined as the quantity of water which the soil contains when completely saturated but freely drained. It may be expressed as volume per cent. or weight per cent. It is usually estimated by the method of Hilgard (14, p. 209), This consists in measuring the quantity of water (volume of weight) which a known amount of the dried soil, contained in a perforated cylindrical brass box* of 6 cm. diameter, and 1 cm. height, soaks up when the box plus soil is placed in a shallow dish of water, and allowed to remain there for an hour. The maximum water-holding capacities of the soils examined by the writer were determined in this way. The magnitude of the result obtained in any one case depends on the mode of packing the soil particles, and on the absorptive capacity for water of the colloidal matter present.

A comparison of the figures in columns 6 and 7 of Tables I-IV shows the general relationship that exists between the amounts of colloidal matter present in the Montserrat soils and their maximum water-holding capacity. Much of

the colloidally absorbed water of soils is available for plant growth. To bring about an increase in the water-holding capacity of a soil, one must add colloidal matter to it. The kind of colloidal matter usually applied in practice is humus. Pen manure and decayed plant residues are composed mainly of humus. The necessity of adding such bulky organic manures to the sandy loam soils of Montserrat as a means of increasing their water-supplying power, has already been urged.

4. *Permeability to water.*

The permeability of a soil to water is defined as the quantity of water which passes per second through a layer of the soil 1 sq. cm. in cross-sectional area and 1 cm. thick, under a head of 1 cm. pressure[9]. It is usually estimated by a percolation experiment.

The values representing the permeabilities of the Montserrat soils examined by the writer were determined as follows :—

Tinned iron tubes of dimensions 16 inches by 1½ inches sectional area were procured. These had a side tube of lead soldered into them at a point 13 inches from one end. In an experiment, the end of a tube furthest away from its side tube was closed with calico, and a one-inch layer of coarse sand was introduced. The tube was then filled to within 2 inches of the outlet of the side tube with the air-dried soil under examination. The soil was poured into the tube through a metal funnel, and the tube dumped occasionally to ensure uniform packing. The tube thus contained, when filled, a column of soil of a length of 10 inches. Several such tubes, filled with different soils, were arranged in descending order in a battery. A slow stream of water was run into the tube at highest level. The water that did not percolate through the soil in this tube, accumulated until a head of height 2 inches above the level of the soil was attained. The surplus water then escaped from the side tube and entered the open end of the next soil tube at lower level, and so on throughout the battery. In this way, a constant head of water was maintained in each tube. The water which percolated through the soils was collected. Measurements of the volume of this water were made every two hours during three successive working days, and the results plotted in graphs. Usually six sets of observations on six different soils were made at one and the same time.

It has been shown by Green and Ampt[9] that determinations of the permeability of soils to water, made by observing the rate of *downward* flow, yield values which decrease in magnitude as the period of percolation increases. This has been accounted for partly by the fact that the finer particles are washed down by the moving water. They recommend that permeability determinations be made by measuring the rate of upward flow. Whereas this recommendation is justified in experiments with the majority of soils, the writer believes that, in case of soils, whose mechanical coustituiion is simple, i.e., soils which are composed mainly of one grade of soil particles, permeability determinations, made by measuring the rate of downward flow, yield results which are significant in comparative experiments. The actual records made with the Montserrat soils indicate that, when the soils have become thoroughly wetted, and when air has been displaced from their pore spaces, the rate of downward flow of water remains practically constant over a fairly prolonged period. Usually this period occurred during the second day of the experiments in the writer's experience. From curves, plotted with time and volume of water collected as co-ordinates, it was found possible to obtain constant and reliable values for the permeabilities of the soils under investigation. These values are recorded in column 8 of Tables I-IV. The formula used in arriving at the values is that given by Green aud Ampt, i.e. $Pw = \frac{V}{t} \cdot \frac{l}{Ah}$ where Pw = the permeability constant; V = volume of water percolating in time t (seconds); l = length of column of soil, in cms.: A = area of section of soil column, in sq. cms.; h = head of pressure, measured from the bottom of the column.

It should be noted that the actual figures in column 8 are 100 time the numbers representing the permeability constants, as expressed in cc. per cc., of soil per second.

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* These boxes (retention cups) may be obtained from the Central Scientific Co. 460, E., Ohio St.; Chicago., U.S.A.

5. Reaction.

This was estimated by Gillespie's method briefly described in the writer's article on soil sourness, ([11], p.56). A neutral soil posesses a pH value of 7·0; an acid soil, a pH value numerically less, and an alikaline soil, numerically greater than 7·0.

6. Organic matter.

The total organic carbon was first estimated by the wet combustion method described by Watts ([26], p·31) In this method, the volume of carbon dioxide evolved when a known mass of the very finely powdered soil is warmed with a mixture of chromic acid and concentrated sulphuric acid is measured in a nitrometer containing mercury. From the volume of gas collected, the percentage of organic matter in the soil can be calculated. The percentage of organic matter in the soil is obtained by multiplying this result by 1·724

7. Soluble humus.

The percentage of humus soluble in ammonium hydroxide solution was estimated by the Grandeau method described by Hall ([10], p·166). Twenty grams of the soil are treated with dilute hydrochloric acid to remove carbonates. The soil is then thoroughly washed on a filter, and transferred to a bottle in which it is agitated with 550 c.c. of a 4 per cent. solution of ammonium hydroxide. After standing over-night, 150 c.c of the supernatant brown liquid are removed with a pipette, and evaporated to dryness in a weighed platinum dish over a water bath. The dish plus residue is weighed, and finally gently ignited to burn off the organic matter. The loss in weight is calculated back to the percentage loss on the original soil. This is taken to represent the percentage amount of ammonia-soluble humus in the soil.

Summary.

Part I.

1. Montserrat is composed of fragmentary volcanic material derived from igneous rocks of sub-alkaline type, chiefly hypersthene andesite.
2. This material has been consolidated into agglomerates, breccias and tuffs.
3. Erosion has produced several conspicuous *talus slopes* which occur chiefly in the southern part of the island. These consist of masses of loose debris overlying the consolidated rocks in layers of varying thicknesses. Water action has carved their surfaces into numerous ravines or ghauts.
4. In the northern part of Montserrat, the consolidated rocks appear near or at the surface, and constitute *shoal rock*. They have suffered intense denudation.
5. In accordance with the geological nature of the substratum, the soils of Montserrat may be classified into *talus soils* and *shoal soils*. The former are soils of transportation, and the latter, sedentary soils. They differ chiefly in the degree to which their subsoils provide free drainage.
6. The shoal soils may be subdivided into *humid upland soils*, *hilly land soils* and *valley soils*. The agencies that have given rise to these sub-types are mainly climatic and topographical in nature.
7. The chief physical features of the types and sub-types of soils enumerated are described in the text, and data obtained in a laboratory examination of representative samples of them are presented in tabular form.
8. The climatology of Montserrat is considered in some detail.

Part II.

9. The problem of the *die-back of lime trees* in Montserrat is presented in historical and general outline
10. The recent view is that the die-back condition is the result of the effect of environmental factors on the growth of lime trees; the problem being physiological rather than parasitological.
11. The methods employed in, and the results obtained by a preliminary ecological reconnaissance of the die-back problemn in the West Indies are presented.
12. The main factors that might have bearing on the problemn are discussed. It is considered that the chief factors responsible for dieback are intimately connected with the water relations between the lime trees and their environment.
13. The effect of variations in water-supply on certain morphological features of lime trees are to be discussed in a separate article by the plant physiologist. (T. G. Mason).

Part III.

14. The outline is given of the laboratory methods used in the examination of soil samples collected in connexion with the investigation.

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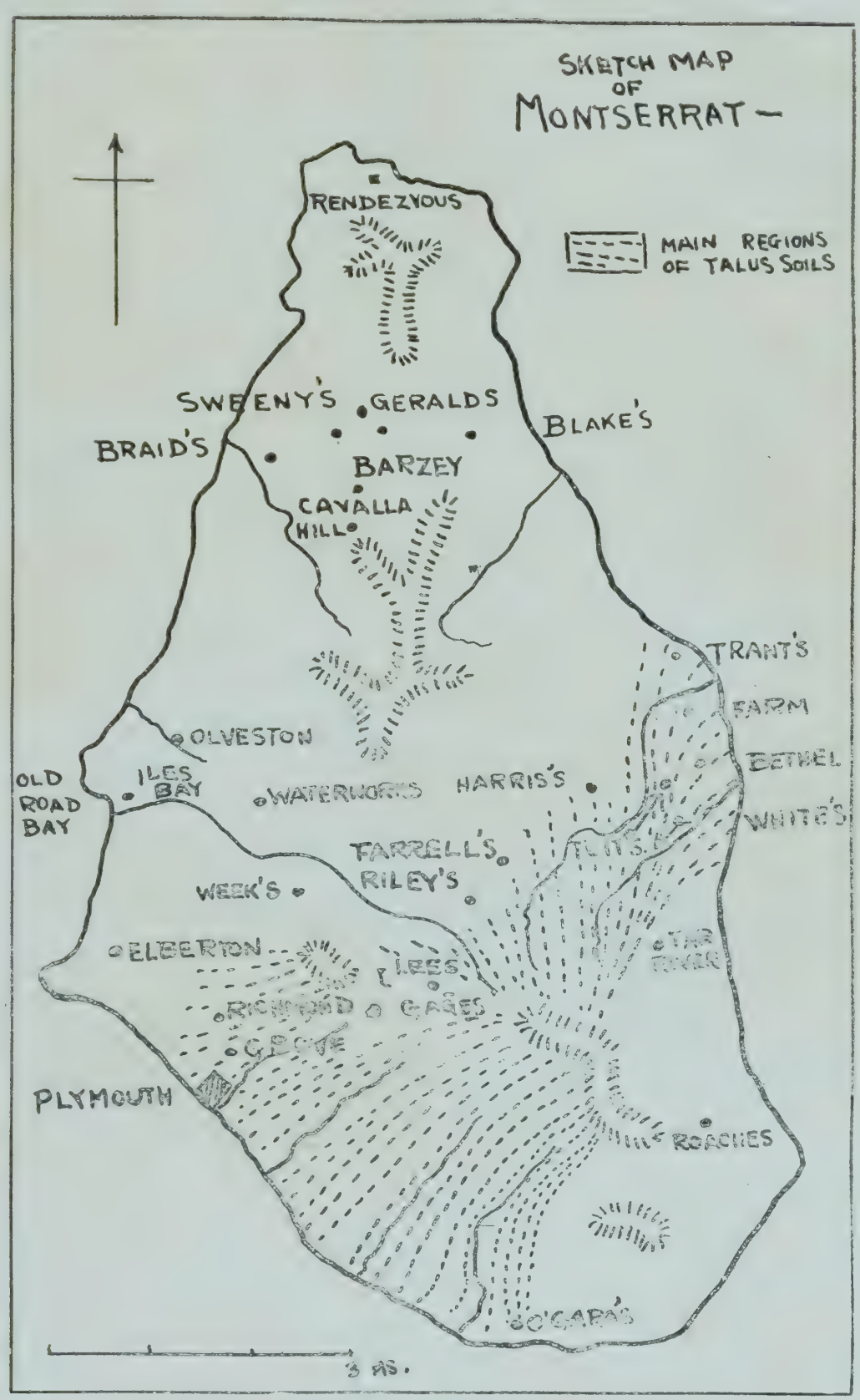

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GROWTH AND CORRELATION IN SEA ISLAND COTTON.

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Introduction.

The studies embodied in the present paper were undertaken in an attempt to ascertain how the growth processes in one part of the cotton plant are related to those in neighbouring parts. It was hoped that the investigation would prove of value not only to the physiologist, but that the results obtained would prove of assistance to the agronomist and the plant breeder.

It will be evident that there are two aspects to the problem. In the first place information is needed concerning the normal growth processes of the plant, and secondly, enquiry must be made as to how the normal course of development in one part is influenced by that in another. It will be patent that both the reproductive and vegetative phases of development ought to receive attention in any attempt which aspires to interpret the development of the organism as a whole. The general scope of the work can, however, be rendered more intelligible after a brief survey has been made of the arrangement of the branch system of the Sea Island cotton plant.

The Arrangement of the Branches.

The plant consists of a central-axis bearing a single leaf at the end of each internode. The leaves are arranged in a $\frac{3}{8}$-spiral. On some individuals the direction of the spiral is right-handed, and in others left-handed; the significance of this condition of antidromy has not yet been elucidated. In the axil of each leaf a bud is present, to one side of it, either to the right or left, according to the direction of the leaf spiral, is another bud. From this extra-axillary bud all the branches are normally developed, the axillary bud remaining either completely dormant, or producing branches of much reduced size. Removal of the branches arising from the extra-axillary buds of course permits their further development.

The dimorphism of the branches is normally well marked, the two types being segregated on distinct parts of the central-axis. The fruiting-branches are first developed somewhere towards the basal region, generally about the ninth node, and extend upwards to the apex. The central-axis and its attendant fruiting-branches will be termed the central-axis system. Reference to Plate 1 will render this intelligible.

The vegetative branches, which normally number from two to four, have their origin in the extra-axillary buds of the nodes immediately below the first fruiting-branch. They are in all

respects exact counterparts of the central-axis system, and will be termed the vegetative-branch systems.

The fruiting-branches bear at the end of each internode a flower-bud, or square as it is sometimes termed, which is situated on the branch in a position nearly opposite the petiole of the leaf. The flower-buds have been considered homologous to the extra-axillary buds from which the fruiting-branches arise. The axillary buds of the fruiting-branches frequently give rise to secondary fruiting-branches (cf. Plate 2), or sometimes to vegetative-branches of much reduced size.

Briefly, then, the plant may be said to consist of a central axis and its associated system of fruiting-branches, and basally a variable number of vegetative-branches, each of which supports a number of fruiting-branches in a manner exactly similar to the central-axis.

Experimental.

The work was carried out on a group of plants, grown for the purpose, on the Experiment Station, St. Vincent. The variety selected for the purpose was isolated by Dr. Harland, and is probably the type best adapted to the very humid conditions under which cotton is grown in St. Vincent. The population consisted of 130 plants, spaced at a distance of 4 feet from one another. The vegetative-branches were removed from alternate plants. As a result of damage sustained by the branches, which was mainly the work of a gale of wind on September 8, the number of plants was finally reduced to 106, so that there remained fifty-four plants in the pruned class and fifty-two in the unpruned. In order to render the subterranean moisture and temperature conditions as uniform as possible, a heavy mulch of cane leaves (*Saccharum officinarum*) was distributed throughout the experimental plot.

The plants were spaced far apart from one another in order that their development should not be influenced by competition between neighbouring plants for light, water, or soil solutes. The wide spacing presents an additional advantage, in that the vegetative-branches tend to grow out from the central axis nearly horizontally, and do not therefore function as a hedge excluding light from the lower fruiting-branches. The possible effect of competition for water and soil solutes between the basal branch systems and the central axis system of the unpruned class is difficult to gauge, and will require further consideration. Another factor that will merit attention when contrasting the development of the central-axis system of the two classes is the effect of those correlation-factors which manifest themselves, for example, in the condition of dominance and subordination of buds. Discussion of their nature will be deferred until the results have been presented.

The Growth Rates.

The length of the central-axis was determined weekly. The measurements were made from an ink mark, situated approxi-

mately 3 centimetres above the surface of the ground, to the apical bud. The first measurements were made on July 8, seventeen days after sowing. On this day the mean distance between the ink mark and the apical bud was 6·8 ± ·10 with a coefficient of variability of 16·1 ± 1·07 in the pruned class and 6·9 ± ·10 with a coefficient of variability of 16·0 ± 1·09 in the unpruned. The

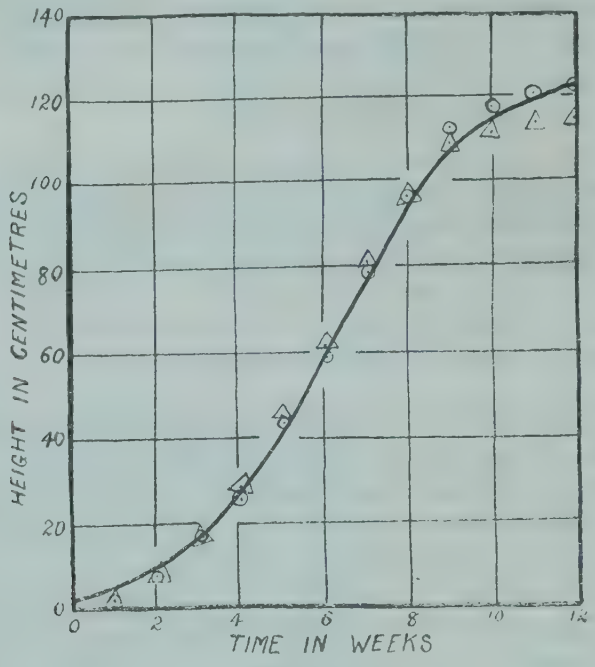

FIG. 1.

Rate of Axis elongation.

The curve represents computed values ; points within circles show observed values for the pruned class, and points within triangles for the unpruned class.

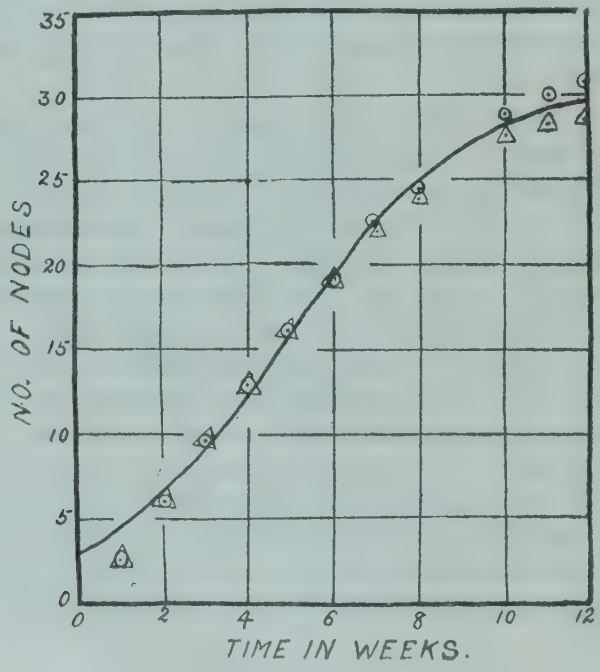

FIG. 2.

Rate of Node production.

The curve represents computed values ; points within circles show observed values for the pruned class and points within triangles for the unpruned class.

results reported in Table I* represent the amount of growth made subsequently.

The rate at which leaves, and therefore nodes, were laid down by the apical meristem of the central-axis was also reckoned weekly, only leaves which had escaped from the apical bud and whose upper surface was visible, were recorded in these determinations. The first record was made on July 8. On this day the pruned class had 5·4 ± ·05 nodes with a coefficient of variability of 10·4 ± ·96, and unpruned 5·2 ± ·06 with a coefficient of variability of 13·2 ± 1·22. The results tabulated (Table II) represent the mean number of nodes produced subsequently on the central-axis.

The rate at which flower-buds accumulated on the fruiting branches of the central-axis system may be seen by reference to Table III. As a very nearly constant time-relation apparently exists between the emergence of the foliage leaf on the fruiting-branch and the appearance of the flower-bud, it was decided to exclude from the determinations flower-buds whose attendant foliage leaves had not developed sufficiently to render their upper surfaces clearly visible. By adopting this convention, buds below a certain age have been eliminated from the results.

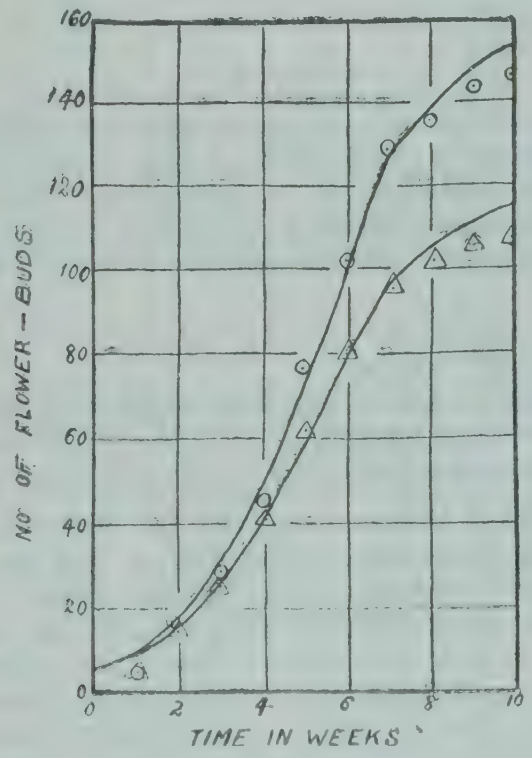

FIG. 3.

Rate of Flower-bud production.

The curves represent computed values; points within circles show observed values for the pruned class, and points within triangles for the unpruned class.

*The tables are grouped together at the end of the paper. The complete data, which is of too extensive a nature for publication, will be sent to other workers, who may be interested.

It should be noted that a certain number of flower-buds are produced on the secondary fruiting-branches (cf. Plate 2), and that these, too, figure in the results.

Inspection of Figures 1 and 3, in which the results for axis elongation and flower-bud accretion are shown graphically, demonstrates that the growth-rates were slow initially, became quicker, and then declined. Such an s-shaped course is characteristic of an autocatalytic reaction. The hydrolysis of sucrose is a type of this class of reaction. The rate is retarded at first by a lack of catalyst, and at the end by a deficiency of substrate; the latter diminishing the rate as a result of mass action. Recently Reed and Holland[3] have shown that the rate of stem elongation in Helianthus approximates closely the course of an autocatalytic reaction. As a result of this correspondence between the growth-rate and a monomolecular reaction, Reed[4],[5] has suggested that growth is some sort of a catalytic process, and that consequently, the organism may be regarded as the end-product of a reaction in which a catalyst acts upon a substrate.

The initial lag in the growth-rate of the nodes is not so marked as in the rate of axis elongation and flower-bud accretion. It will be of interest nevertheless, to inquire how closely the experimental results approximate the values calculated from the differential equation

$$\frac{dx}{dt} = k\,x\,(a-x)$$

which is characteristic of an autocatalysed reaction. In this equation x represents the length of the central-axis, the total number of flower-buds or of nodes at any time t; a is the final height, number of buds or of nodes as the case may be; and k is a constant. When integrated the above equation becomes

$$\log.\frac{x}{a-x} = K\,(t-t')$$

where $K = ak$ and t' is the time at which the central axis has grown to half its final length, or at which half the number of flower-buds or of nodes have been formed, that is to say, when $x = \frac{a}{2}$. By means of tables prepared by Robertson[6], the constants K and the theoretical values of x are readily obtained from the observed values. The values taken for a and t', and also the derived values of K, may be seen in Tables I, II, and III. It will be observed that the calculated curves (Figures 1, 2, 3) which are constructed from the computed values, agree remarkably closely with the experimental data. The rate of the node production is, however, practically linear for the first five or six weeks, and is not therefore especially suggestive of autocatalysis. Though the correspondence between the observed and the theoretical values is admittedly very striking, yet the assumption that growth is some sort of a catalytic process is quite unwarranted. An examination, for example, of the time-relations of the rates of axis elongation and flower-bud formation lends no support to this hypothesis. This will be considered in the next section.

The Weekly Increments in Growth.

The amount of elongation observed in the central-axis at intervals of seven days is recorded in Table IV. In Tables V and VI the weekly rates of flowe -bud and flower production will be seen. The data are presented graphically in Figure 4. Inspection of the graphs demonstrates very clearly the retardation in growth-rate of the central-axis which attends the initiation of

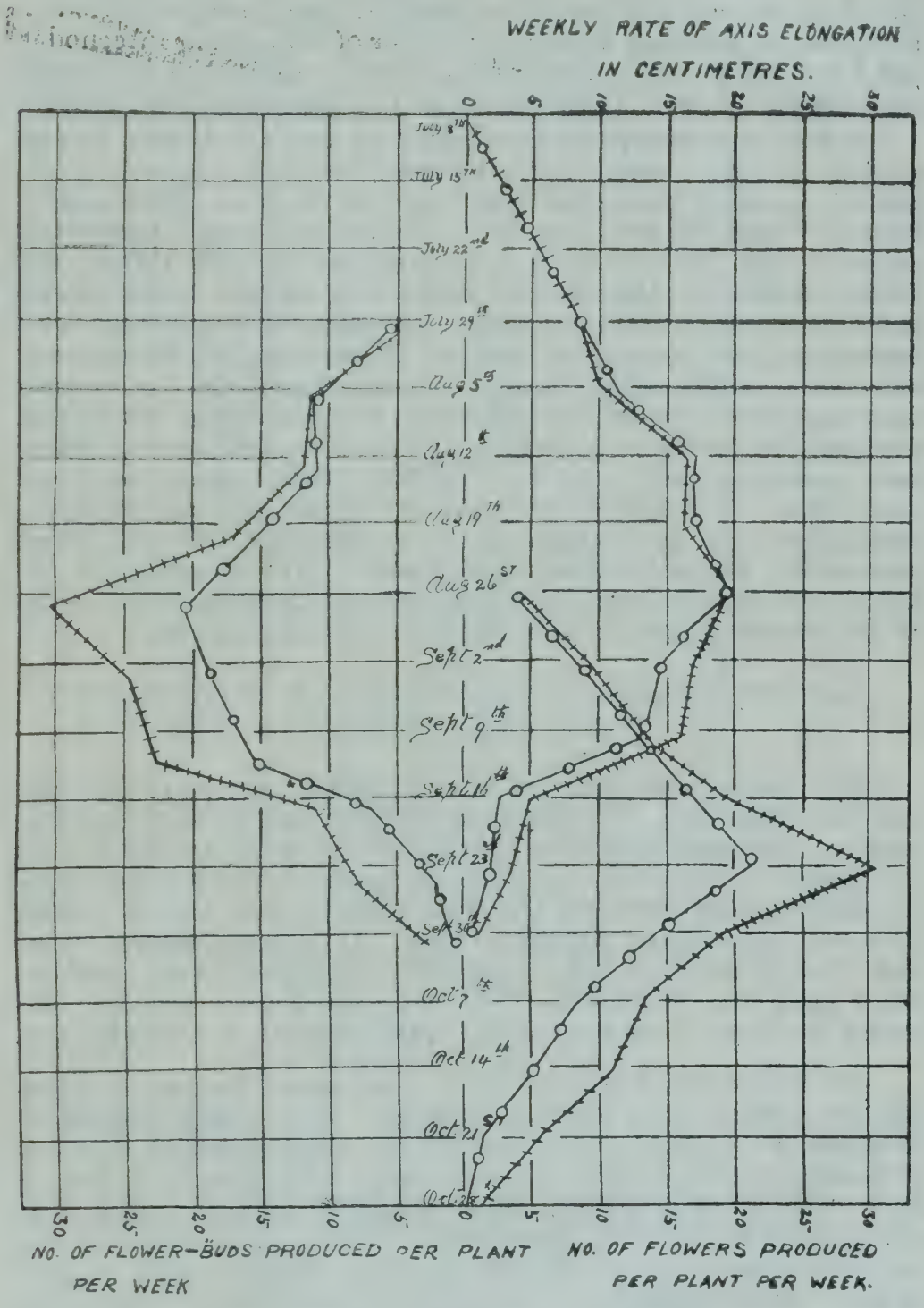

Fig. 4.

Showing weekly rate of axis elongation, flower-bud and flower production. Unpruned Class —o—o—o—. Pruned Class —|—|—|—|—.

flower formation and consequently of fruit development. This cannot be considered indicative of the action of a catalyst on a substrate, or that the decline in the growth-rate is due in any way to mass action. It does suggest that senescence in the central-axis of the cotton plant is associated with a downward translocation of carbohydrates, and probably other growth-promoting substances, from the apical region of the system to the basal fruiting-branches on which the first fruits are developed. The lag at the commencement of the growth period is doubtless the result of a smaller number of elongating internodes, and a relative paucity in the carbohydrate supply, the inevitable consequence of the development of the photosynthetic system.

Before considering the developing of the central-axis branch systems of two classes, a word should be said concerning the relative rates of flower-bud and flower production Reference to Tables V and VI will show that the rate of flower production exceeded that of flower-bud production in the third and fourth weeks in the pruned class, and in the third, fourth and fifth weeks in the unpruned. An excess of flower-buds over flowers might of course be ascribed to shedding of flower-buds, but how, it will be asked, can the reverse occur. On the assumption that the convention adopted in reckoning flower-buds was justified, and that consequently, the observed rates of flower-bud accretion are not less reliable than those of flower production, it would seem that the greater rates of flower production may have been due to a shortening of the period required for the maturation of the flower. As the subject is one which will receive attention elsewhere, and is beyond the scope of the present paper, further discussion is unnecessary.

The Development of the Central-Axis System in the Two Classes.

The results attending the removal of the vegetative-branches will be considered. The contrast between the rates of development of the central-axis system in the two groups is shown by the graph in Figure 5. The curves represent the relative rates of development between the two classes, and are of course obtained by plotting out their ratios. It will be evident, that had the removal of the vegetative branches been without effect upon the development of the central-axis system, the curves in Figure 5 ought to have approximated a straight line.

At this stage of the enquiry a word should be said concerning the manner and time of pruning. The young vegetative branches were removed the day prior to that on which the first reckoning of the number of nodes was mad·, that is to say on July 29. At this period these branches ranged from 0·14 centimetres in length. The shoots, which, as a result of the pruning, commenced to develop from the axillary buds, as well as from the extra-axillary buds, were removed at the end of the ensuing week. The last pruning was carried out on August 12, and consisted mainly in the removal of vegetative branches originating in the axillary buds in the zone of basal fruiting

branches. All the upper axillary buds, when developing at all, produce greatly reduced fruiting branches. In some strains, however, the axillary buds give rise almost exclusively to small vegetative branches; this character, it may be noted, is one of considerable cultural importance under humid conditions. The period of pruning thus extended over a period of three weeks, and is noted in Figure 5 by a series of crosses.

Inspection of the graph will show that the rate of node production in the pruned class, which prior to the removal of the vegetative branches had been somewhat less than in the unpruned, exceeded the latter on the fourth week. This augmented rate of node production was naturally followed by a greater rate

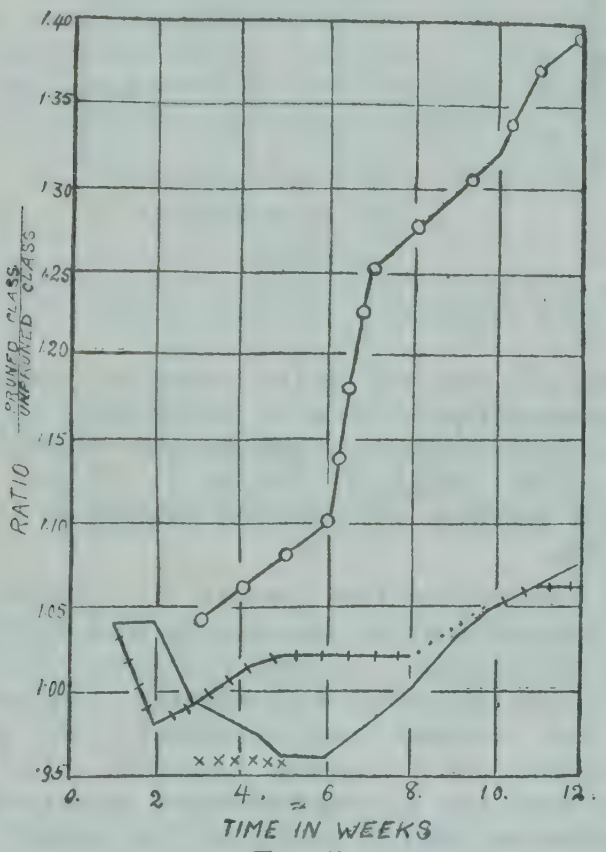

FIG. 5.

Exhibiting relative rates of growth in two classes.

Flower-bud Accretion—o—o—o—
Node Production—|—|—|—|—|—
Axis Elongation ———
Period of pruning xxxxxx

of stem elongation as a result of the greater number of elongating internodes.

Flower-bud production in the pruned class exceeded that in the unpruned throughout the period, but did not display a very marked superiority until the seventh week.

The rate at which flower-buds were produced by the axillary fruiting branches was not ascertained; it may be noted though, that the mean number of flowers produced on these branches by

the plants receiving pruning was 5·6 ± ·55 with a coefficient of variability of 81·3 ± 8·03, whereas in the unpruned class the number was 3·6 ± ·29, and the coefficient of variability was 98·8 ± 11·21.

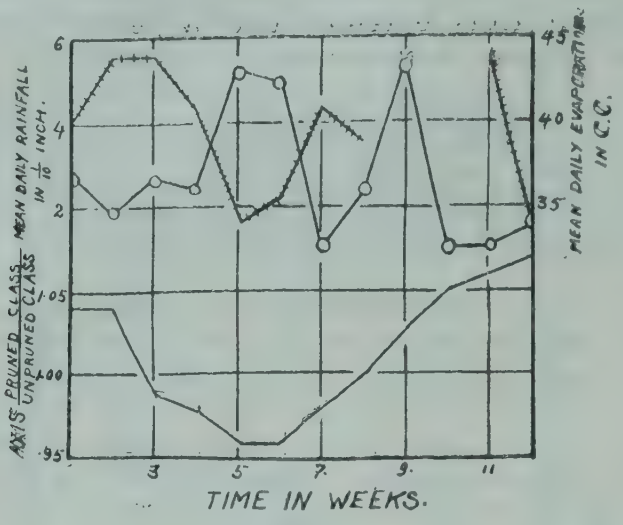

FIG.6.
Showing relative rates of axis elongationin the two classes.—Rainfall—o—o—and Evaporation—|—|—

To sum up, the removal of the vegetative-branches resulted in a greatly increased production of flower-buds, and of somewhat higher rates of axis elongation, and of node production. It will already have been noted (cf. Tables IV, V, and VI) that the pruning did not produce any marked change in the variability of the population.

It will be profitable at this juncture to compare the relative rates of axis elongation in the two classes with the fluctuations in the aridity of environment. A priori considerations suggest that the growth-rate of the group with adherent vegetative branches would have been checked relative to that of the pruned plants during the periods of decreasing humidity. The weekly rates of evaporation from the Livingston black spherical atmometer, and of precipitation, both of which are expressed on the daily basis, are shown in Figure 6 for comparison with the curve showing the relative rates of central-axis elongation in the two classes. The rates of evaporation were not available for the eighth and ninth weeks.

Inspection of these curves will make it clear that the additional water strain which might have been anticipated from the presence of the vegetative-branch systems, has been responsible for no sensible retardation of the growth-rate of the unpruned class during the periods of greatest aridity. It may accordingly be surmised that the reduced development of the central-axis of the unpruned class was not due to a water shortage, or to any factor associated with competition for water between the different parts of the plant. I should also be observed that the rates of node production and flower-bud

formation bear no constant relation to the changes which occurred in the aridity of the environment.

The Number of Nodes on the Fruiting-Branches.

Morphogenetic considerations suggest three factors to which the augmented rates of flower-bud production in the pruned class could be ascribed. Firstly it will be patent that the greater rate of node production in this class, to which reference was made in the preceding section, must have involved a concomitant acceleration in the rate of fruiting-branch formation for fruiting-branch development, when once initiated, takes place from the extra-axillary buds of every node of the central-axis.

The second factor, responsible for the difference in the rates of flower-bud formation in the two groups, was a greater development in the pruned class of secondary fruiting-branches (cf. Plate 2). The mean number of flower-buds produced per plant

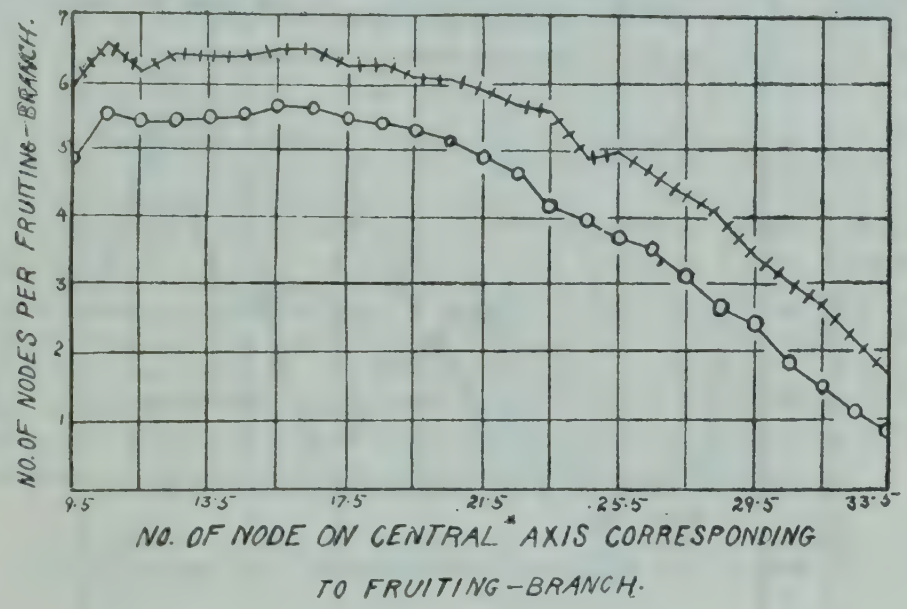

Fig. 7.

Showing mean number of nodes on successive fruiting-branches in the two classes. Unpruned :— —o—o—o— Pruned :— —|—|—|—|—

on these branches in the latter class was 17·9, whereas in the unpruned class there were only 2·0.

The most important factor, however, may be traced to a larger number of nodes on the individual fruiting-branches; for at every node on the fruiting-branches, it will be remembered, there is a flower bud. The number of nodes on successive fruiting-branches is shown in Table VII; the results are presented graphically in Figure 7. It will be observed that the pruned class exhibits a well marked superiority over the unpruned in this respect. A perfectly regular decline in the number of nodes of the apical fruiting-branches will also be detected. These observations naturally prompt inquiry as to the nature of the factors which determine the number of nodes on a fruiting-branch. Any

hypothesis which may be formulated ought not only to explain why there is a reduction in the number of nodes on the apical fruiting-branches, but should also account for the reduction in the number of nodes, which is associated with the development of the vegetative-branches. This is evidently another phase of the problem presented by the decline in the growth-rates of both classes, and by the augmented development of the central-axis system of the group that received pruning.

Coefficients of Correlation between the Number of Nodes on Neighbouring Fruiting-Branches.

The degree of correlation between the number of nodes on neighbouring fruiting branches will now be considered. The coefficients have been calculated, and are recorded in Table VIII. The results are presented graphically by overlapping means in Figure 8. It will be observed that the coefficients are all positive and many times their probable errors. It will also be seen that'

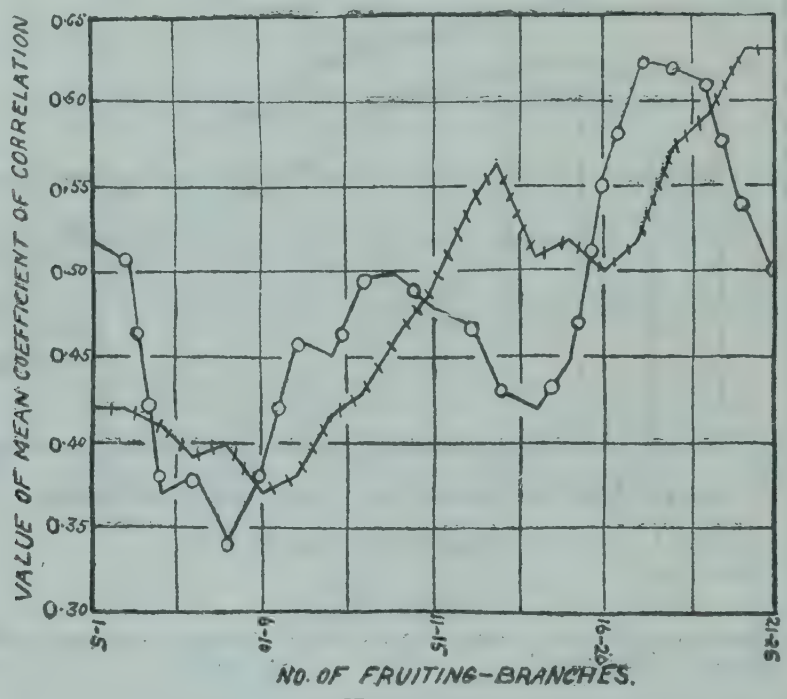

Fig. 8.

Showing mean value of coefficient of correlation for successive over lapping groups of five fruiting-branches.

there is a well-defined tendency in both groups for the correlation between the number of nodes on neighbouring fruiting-branches to be greater in the apical zone of fruiting-branches, where of course the number of nodes on the fruiting-branches is less than in the lower zones. This and the positive nature of the coefficients may be held to indicate the presence of a factor, which limits the number of nodes on all the fruiting-branches and that its influence becomes more marked on the fruiting-branches in the apical region. If this correlation-factor is associated with the development of fruit by the lower fruiting-branches, it would seem that the development of the latter, too, is limited by their

own activity in producing fruit. In short, it would appear that the number of nodes on a fruiting-branch is determined by the development of fruit both on itself and on the other branches of the system. This view is supported by the fact that the removal of fruit results in the greater increase in the number of nodes on the fruiting-branches. It is of some importance to note that the natural shedding of fruit may tend, under certain conditions, to bring about the same result; this, it is patent, is but an illustration of what has long been known under the name of 'compensatory growth.'

Thus far no attempt has been made to account for the more limited development of the fruiting-branches in the group of plants with adherent vegetative-branches. Though the reduction in the number of nodes on the fruiting-branches in the apical region of the central-axis system has been associated with the development of fruit on the lower fruiting-branches, yet there are objections to ascribing the more limited development of the fruiting-branches of the central-axis system of the unpruned plants to the production of fruit by the vegetative branches. The main objection of course is that the pruned class exhibited a well-marked superiority in the production of flower-buds before the appearance of fruit on the vegetative-branches of the unpruned group. It seems necessary to assume, therefore, that the development of the vegetative branches, irrespective of the development of fruit, in some way introduces a factor which limits the development of the fruiting-branches of the central-axis system. It is of interest in this connexion to note that the coefficients of correlation between the basal fruiting-branches tend to be somewhat smaller in the unpruned group. This is possibly the expression of a factor, introduced by the growth of the vegetative branches, which inhibits fruiting-branch development.

The Rate of Axis Elongation in the Absence of Developing Fruit.

The substance of the preceding sections may now be summed up. The decline in the development of the fruiting-branches in the apical region of the central-axis system, the retardation, in the rate of axis elongation, or of node production by the apical meristem, may all be traced to the presence of a common factor introduced by the development of fruit on the basal fruiting-branches. The senescence of the central-axis system as a whole seems to find its most ready interpretation in this way, and need not therefore be ascribed to the action of a catalyst on a substrate. On the other hand the reduction in the development of the central-axis system resulting from the presence of the basal vegetative-branches systems, cannot be specifically associated with fruit development by the latter, but must be ascribed, at least in part, to the mere vegetative development of these branches. It becomes essential, therefore, to enquire whether the decline in the growth-rate of the central-axis is necessarily dependent on the development of fruit, or whether it may not occur as the

result of the vegetative development of fruiting-branches from which fruit production has been prevented, by the removal of flowers.

The plants employed in this experiment were approximately eleven weeks old at the time the measurements first recorded were made. All flowers, fruit, and vegetative-branches had been removed nine days previously. There were ten plants in

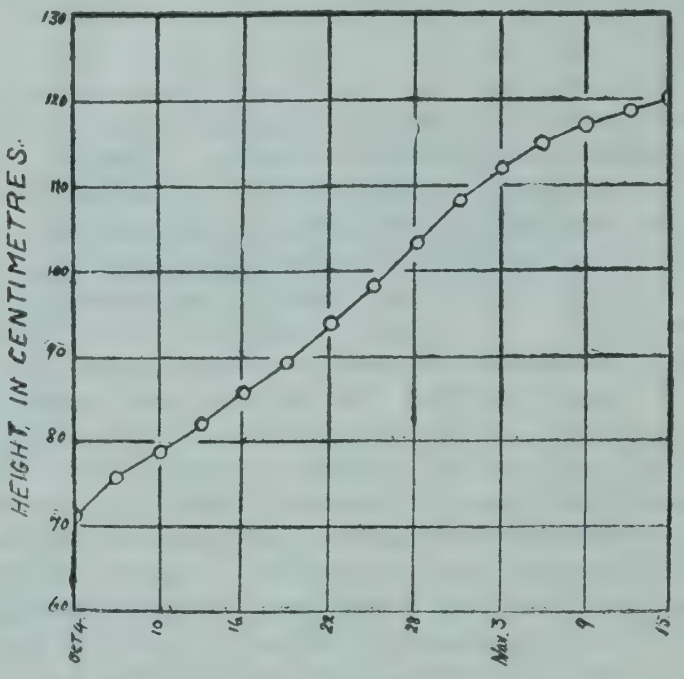

FIG. 9.

Growth-rate of plants from which flowers and fruit were removed.

all, and the measurements were made daily for a period of forty-three days; flowers were removed daily as they appeared, so that there were no developing fruit on the plants. The results are presented graphically for three day intervals in Figure 9. The fruiting-branches as a result of the flower pruning, of course, developed a much larger number of nodes than would normally have occurred. Reference to the graph will show that even in the absence of developing fruit a sensible decline occurred in the growth-rate, though this was admittedly considerably less pronounced than if flowers had not been removed. It may be therefore tentatively concluded that a decline in the growth rate is not necessarily associated with fruit development, but may occur solely as the result of the vegetative development of the fruiting-branches.

DISCUSSION.

Before discussing the significance of the results reported in the preceding sections, it will be well, in order to remove any possible confusion in the mind of the reader, briefly to state again their contents.

Two groups of cotton plants were grown, from one of which the vegetative-branches were removed The rate of development of the central-axis system was compared in the two groups. The three phases of growth which were considered, were the elongation of the central axis, the production of nodes by the apical meristem of the central-axis, and the formation of the flower-buds on the fruiting-branches. In all three cases the experimentally obtained values, for both groups, were in good agreement with the theoretical values computed from the equation charateristic of an autocatalytic reaction.

It was emphasized that the mere correspondence between the observed and the computed values could not warrant the conclusion that growth was some sort of a catalytic process; or to state the case in other terms, that organism was the end-product of a reaction in which a catalyst acted upon a substrate. The decline in the growth-rate of the central-axis, which accompanied the initiation of fruit production seemed to suggest, on the contrary, that senescence of the central axis system was associated with a downward translocation of carbohydrates, and possibly other growth-promoting substances, from the apical region to the developing fruit. The latter explanation, it may be remarked, involves the assumption that the cessation of activity in the apical meristem is due to the existence of a correlating factor of some sort, which operates to deflect the supply of assimilates from the apical bud to the developing fruit; and that consequently, renewed activity of the apical bud should attend ts isolation from the growth-inhibiting influence of the developing fruit. It is of some interest, therefore, to find that the apical bud does exhibit renewed activity when 'budded' on to a young cotton plant.

The removal of the vegetative-branches was found to permit, a somewhat more rapid rate of axis elongation and of node production. The rate of flower-bud formation in the pruned class was shown to be considerably greater than in the unpruned. Examination of the fruiting-branches revealed the fact that this was chiefly the result of a greater number of nodes on the individual fruiting-branches.

It was also ascertained that the decline in the rates of axis elongation and of node production by the apical meristem of the central-axis, which was exhibited by both groups, was accompanied by a perfectly regular reduction in the degree of development of the apical fruiting-branches. This and the more limited development of the fruiting branches of the group of plants with adherent vegetative-branches prompted enquiry into the nature of the factors limiting fruiting-branch development.

Calculation of the coefficients of correlation between the number of nodes on neighbouring fruiting-branches demonstrated that not only were the coefficients all positive, but that their values were, on the whole, greater in both groups for the apical than for the basal zone of fruiting branches This was considered to indicate the presence of some factor which tended to limit the development of all fruiting-branches, and that its influence

became more marked as development proceeded. It was accordingly suggested that the development of all the fruiting-branches was limited, on the one hand, by their own activity in producing fruit, and that the more reduced development of the apical fruiting-branches was due to the influence of fruit maturing on the basal fruiting-branches. This view seemed to find support in the observation, that the removal of the flowers as they appeared, and consequently the absence of developing fruit, resulted in a more extended development of the fruiting-branches.

Comparison of the coefficients of correlation in the two classes showed that their values were initially somewhat smaller in the group from which the vegetative-branches had been removed. This and the more reduced development of the fruiting branches in this class suggested the introduction of an additional factor, inhibiting the development of the fruiting branches in the unpruned class. It was emphasized that the more limited development of the fruiting-branches in this class could not be specially associated with the development of fruit on the vegetative-branches. By daily measurements of a group of plants from which all vegetative-branches and fruit had been removed, it was found that the decline in the growth rate of the central-axis, though deferred, was none the less marked; from which it was tentatively concluded that the mere vegetative growth, either of the fruiting-branches or of vegetative-branches, exerted a retarding effect on the growth of the central-axis.

The nature of the growth-inhibiting factor, to which the growth correlations just described have been referred, must now be considered. It was shown that the more limited development of the central axis in the group of plants with adherent vegetative-branches could not be ascribed to a greater water strain than that which prevailed in the pruned group; even though, as was pointed out, a more pronounced water-shortage might legitimately have been expected as the result of the greater transpiring surface due to the presence of the vegetative-branch systems.

Nevertheless, it might possibly be argued, that competition for inorganic electrolytes in the ascending sap between the branch systems might have been responsible for the more limited development of the central-axis system of the unpruned plants. It might also appear feasible to explain the reduced development of the apical portion of the central-axis system in both groups as being due to a prior claim by the basal fruiting-branches and their developing fruit on the supply of inorganic solutes in the ascending sap. It will be evident that this hypothesis assumes, since the view that competition for water was found untenable, that the solutes and solvent, which constitute the soil solution, move independently upwards after their entry into the plant. Though such an assumption presents obvious difficulties, it cannot be easily dismissed. It would not therefore be unjustifiable to conclude from this line of argument that the experimental results might be reconciled with the hypothesis, that

growth, whether in the apical portion of the central axis system of both groups, or in the central-axis of the pruned group, was checked as a result of a limited supply of electrolytes. Difficulties, however, are encountered when the attempt is made to harmonize this view with the fact that the coefficients of correlation between neighbouring fruiting-branches were greater in the apical than in the basal region of the central-axis system. The assumption that the reduced development of the apical region is due to the production of a growth-inhibitor by the basal fruiting-branches, and that the more limited development of the central-axis system of the unpruned groups is due to the production of a growth-inhibiting substance by the vegetative-branches, is fraught with even greater difficulties than those attending the electrolyte hypothesis. The chief objection to this assumption is of course that the growth-inhibitor should depress growth wherever it is produced, for there it ought also to be in greatest concentration.

It would seem more plausible to assume that the growth promoting substances tend to be withdrawn from the central axis system as a result of the unrestricted growth of the vegetative branches, and that the senescence of the central axis system is similarly ascribable to deflection of these substances to the basal fruiting-branches. Harvey [1] has suggested that these growth-promoting substances may include such bodies as the chromogens of Palladin, which are produced by all cells, and are diffusible. There can be little doubt that the movement of such substances is intimately associated with the translocation of carbohydrates.

Though the existence of such substances would doubtless account for the correlation in the growth processes which have been considered in the course of these studies, it will be evident that, until their nature, and the mechanism of their translocation have been elucidated, further speculation cannot be profitable.

Summary.

(1)—The development of the central-axis system of branches was studied in two groups of cotton plants, from one of which the vegetative-branch systems were removed.

(2)—The rate at which the central-axis elongated, of node production by the apical meristem, and of flower-bud formation on the fruiting-branches, was found in all three cases to approximate closely the course of an autocataly tic reaction.

(3)—It was emphasized that the simulation of an autocatalytic reaction was probably quite illusory. Examination of the coefficients of correlation between the number of nodes on neighbouring fruiting-branches suggested, on the contrary, that the decline in the growth rate of the central-axis system was due to the presence of a correlating-factor. The latter was associated with the development of fruit on the basal fruiting-branches, and to a lesser extent with the vegetative growth of these branches.

(4)—The removal of the vegetative-branches resulted in a greater development of the central-axis system.

(5)—It was found impossible to harmonize the more limited growth of the central-axis system, exhibited by the unpruned group, with the view that development was checked, as a result of competition with the vegetative-branches for either the solutes or the solvent of the soil solution.

(6)—It was suggested that not only the more limited development of the unpruned group, but also the decline in the growth-rate of both groups, was due to the removal of growth-promoting substances by the vegetative-branches and the basal fruiting-branches respectively. It was pointed out that the movement of these substances was probably associated with the translocation of carbohydrates.

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Arrangement of Branch Systems in Cotton Plant.

PLATE 1

Primary Fruiting-branch with Secondary Fruiting-branch.

PLATE 2.

TABLE I.—AXIS ELONGATION.

Date.	t weeks.	x observed pruned class.	x observed unpruned class.	x calculated a = 126 t' = 6·1 K = ·26
July 8 ...	0	0	0	3·2
,, 15 ..	1	2·8	2·7	5·7
,, 22 ...	2	8·5	8 2	9·9
,, 29 ..	3	17·0	17·1	17·0
August 5 ...	4	27·4	28 1	27·9
,, 12 ..	5	43·7	45·3	43·0
,, 19 ...	6	60·1	62·3	61·1
,, 26 ..	7	79·8	81·8	79·6
Sept. 2 ...	8	97·1	96·8	95·4
,, 10 ...	9·14	113·0	109·9	108·5
,, 16 ...	10	117·7	112·3	114·9
,, 23 ...	11	121·3	114·4	119·6
,, 30 ...	12	122·3	114·8	122·5

TABLE II.—NODE PRODUCTION.

Date.	t weeks.	x observed pruned class.	x observed unpruned class.	x calculated a = ·31 t' = 4·8 K = ·20
July 8 ...	0	0	0	3·1
„ 15 ...	1	2·8	2·7	4·6
„ 22 ...	2	6·0	6·1	6·9
„ 29 ...	3	9·7	9·8	9·4
August 5 ...	4	13·2	13·1	12·7
„ 12 ...	5	16·3	16·0	16·2
„ 19 ...	6	19·5	19·2	19·7
„ 26 ...	7	22·5	22·1	22·7
Sept. 2 ...	8	24·8	24·3	25·2
„ 16 ...	10	29·1	27·7	28·4
„ 23 ...	11	30·1	28·3	29·3
„ 30 ...	12	30·5	28·8	29·9

TABLE III.—FLOWER-BUD PRODUCTION.

Date.	t weeks.	Pruned class		Unpruned class.	
		x observed	x calculated a = 160 t' = 5·2 K = ·29.	x observed	x calculated a = 120 t' = 4·95 K = ·28
July 23	0	0	4·8	0	4·8
„ 30	1	5·5	9·1	5·3	8·6
August 6	2	17·1	16·8	16·2	15·7
„ 13	3	29·2	29·9	26·9	26·5
„ 20	4	46·2	49·6	41·9	42·1
„ 27	5	77·0	74·7	61·8	61·0
Sept. 3	6	102·2	103·8	80·5	79·6
„ 12	7·29	125·2	128·2	96·1	98·3
„ 17	8	136·4	138·6	103·2	105·2
„ 24	9	144·4	148·3	105 5	111·8
October 1	10	146·9	153·8	105·9	115·6

TABLE IV.—WEEKLY INCREMENTS OF AXIS ELONGATION.

Date.	Pruned class.		Unpruned class.	
	Weekly increments.	Coefficient of variability.	Weekly increments.	Coefficient of variability.
July 15	2·8±·08	29·8± 2·10	2·7±·10	37·7± 2·83
„ 22	5·7±·15	29·4± 2·07	5·5±·17	32·1± 2·32
„ 29	8·5± 17	21·3± 1·44	8·9±·20	24·4± 1·71
August 5	10·4± 16	17·4± 1·16	11·0±·17	15·8± 1·07
„ 12	16·3±·21	14·1± 93	17·2±·22	13·6± ·92
„ 19	16·4±·12	7·8± ·50	17·0±·16	9·8± ·65
„ 26	19·7± 18	9·9± ·64	19·5±·14	7·5± ·50
Sept. 2	17·3± 28	18·0± 1·21	15·0±·27	19·3± 1·32
„ 10	15·9±·32	22·1± 1·50	13·1±·31	26·6± 1·88
„ 16	4·7±·25	55·9± 4·63	2·4±·16	69·3± 6·42
„ 23	3·6±·19	54·9± 4·51	2·1± 13	68·9± 6·35
„ 30	1·0±·21	113·1±13·85	·4±·06	150·6±23·44

TABLE V.—WEEKLY INCREMENTS OF FLOWER-BUD ACCRETION.

Date.	Pruned class.		Unpruned class.	
	Weekly increments.	Coefficient of variability.	Weekly increments.	Coefficient of variability
July 30	5·5± ·30	59·0± 4·99	5·3±·32	64·2± 5·74
August 6	11·6± ·28	25·9± 1·79	10 9±·35	34·0± 2·49
„ 13	12·1± ·24	21·9± 1·49	10 7± 30	29·5± 2·11
„ 20	17·0± ·38	24·2± 1·66	15·0±·32	22·8± 1·59
„ 27	30·8± ·98	34·8± 2·52	19·9±·70	36·2± 2·68
Sept. 3	25·2±1·03	44·5± 3·42	18·7±·78	44·4± 3·47
„ 12	23·0±1·01	48·0± 3·76	15·6±·70	47·8± 4·60
„ 17	11·2± ·58	56·9± 4·74	7·1±·52	80·. ± 8·01
„ 24	8·0± ·61	82·5 ± 8·22	2·3±·26	122·0±15·89
October 1	2·5± ·36	150·7±22·83	·4±·08	281·5±76·17

TABLE VI.—WEEKLY INCREMENTS IN FLOWER FORMATION.

Date.	Pruned class.		Unpruned class.	
	Weekly increments.	Coefficient of variability.	Weekly increments.	Coefficient of variability.
August 26	4·3±·23	58·7± 4·95	3·9 ±·21	57·9± 4·86
Sept. 2	9·2±·30	35·3± 2·56	8·8±·34	42·5± 3·22
„ 9	13·3±·30	24·9± 1·71	12·2±·36	30·9± 2·18
„ 16	19·5±·38	21·3± 1·44	17·3±·42	26·5± 1·84
„ 23	30·3±·70	25·2± 1·73	21·6±·61	30·6± 2·16
„ 30	19·0±·49	28·0± 1·95	14·2±·38	29·4± 2·07
Oct. 7	13·3± 49	4·03± 3·00	8·5±·45	57·3± 4·79
„ 14	11·0±·59	58·4± 4·92	5·0±·38	83·1± 8·32
„ 21	5·5±·49	86·9± 8·93	1·3±·20	165·7±27·39
„ 28	1·4±·23	176·4=30·75	·3±·06	268·3±68·28

TABLE VII.—NUMBER OF NODES ON SUCCESSIVE FRUITING-BRANCHES

No. of fruiting-branch.	Pruned class.		Unpruned class.	
	Mean No. of node on central axis from which fruiting-branch was developed.	Mean No. of nodes on fruiting-branch.	Mean No. of node on central-axis from which fruiting-branch was developed.	Mean No. of nodes on fruiting-branch.
1	9·5	5·9 ± 11	9·3	4·8 ± ·12
2	10·5	6 6 ± ·06	10·3	5·5 ± ·10
3	11·5	6·2 ± 06	11·3	5·4 ± ·07
4	12·5	6·4 ± ·07	12·3	5·4 ± ·09
5	13·5	6·3 ± ·07	13·3	5·5 ± 07
6	14 5	6·4 ± ·07	14·3	5·5 ± ·07
7	15·5	6·5 ± ·08	15 3	5·7 ± ·07
8	16·5	6·5 ± ·07	16·3	5 6 ± ·08
9	17·5	6·3 ± ·09	17·3	5·5 ± ·03
10	18·5	6·3 ± ·08	18·3	5·4 ± ·08
11	9·5	6·1 ± ·11	19·3	5·3 ± ·09
12	0·5	6·2 ± ·10	20·3	5·2 ± ·11
13	1·5	5·9 ± ·10	21·3	4·9 ± ·08
14	2·5	5·7 ± ·10	22·3	4·7 ± ·10
15	3·5	5·6 ± ·10	23·3	4·2 ± ·09
16	4·5	4·9 ± ·12	24·3	4·0 ± ·11
17	5 5	5·0 ± ·13	25·3	3·7 ± ·10
18	6·5	4·7 ± ·13	26·3	3·5 ± ·11
19	7·5	4·3 ± ·13	27·3	3·1 ± ·12
20	8·5	4·1 ± ·13	28·3	2·7 ± ·11
21	9·5	3·4 ± ·13	29·3	2·4 ± ·10
22	0·5	3·1 ± ·13	30·3	2 1 ± 09
23	1·5	2·7 ± ·11	31·3	1·5 ± ·10
24	2·5	2·2 ± ·11	32·3	1·2 ± ·09
25	3·5	1·7 ± ·10	33·3	·8 ± ·07

TABLE VIII.—COEFFICIENTS OF CORRELATION BETWEEN NEIGHBOURING FRUITING-BRANCHES.

No. of fruiting-branches.	Coefficients of correlation.		No. of fruiting-branches.	Coefficients of correlation.	
	Pruned class	Unpruned class.		Pruned class.	Unpruned class.
1–2	0·32±·082	0·47±·073	13–14	0·53±·066	0·47±·072
2–3	0·26±·085	0·44±·075	14–15	0·49±·070	0·52±·068
3–4	0·29±·084	0·45±·074	15–16	0·54±·065	0·43±·076
4–5	0·40±·077	0·43±·076	16–17	0·51±·068	0·40±·078
5–6	0·33±·082	0·33±0·83	17–18	0·60±·059	0·66±·053
6–7	0·41±·076	0·16±·091	18–19	0·63±·055	0·48±·072
7–8	0·39±·078	0·39±·079	19–20	0·57±·062	0·75±·041
8–9	0·60±·059	0·42±·077	20–21	0·41±·076	0·55±·065
9–10	0·41±·076	0·64±·055	21–22	0·62±·057	0·51±·069
10–11	0·32±·082	0·56±·064	22–23	0·55±·064	0·50±·070
11–12	0·43±·075	0·49±·071	23–24	0·54±·065	0·19±·090
12–13	0·38±·079	0·39±·079	24–25	0·41±·076	9·52±0·68

REPORT ON THE PREVALENCE OF SOME PESTS AND DISEASES OF CROPS IN THE WEST INDIES DURING 1920.

(Compiled from Reports of the Local Agricultural Officers.)

This is the twelfth report in this series. The latest previous report, that for the year 1919, appeared in the *West Indian Bulletin*, Vol. XIX, No. 1, p. 18.

The present report covers the period January to December 1920, and has been prepared in the same way as in previous years, from information supplied by the Agricultural Officers in the several islands.

ENTOMOLOGIST'S VISITS. During 1920 the Entomologist paid a lengthy visit to the Leeward Islands (January 6 to March 18). This visit was largely devoted to a study of the hard-back grub in Antigua, but a stop of a few days was made at Dominica in connexion with an outbreak of *Orthezia insignis* on limes. St. Kitts and Nevis were also visited.

The brown hard-back (*Lachnosterna antiguae*, Arrow) in Antigua, formed the subject of a paper in the *West Indian Bulletin*, Vol. XIX, p. 1.

The visit to St. Kitts and Nevis was in connexion with general entomological matters concerning the principal crops, sugar-cane and cotton.

The Entomologist attended the Official Conference of Economic Entomologists held in London, June 1 to 11.

In November the pink bollworm of cotton (*Platyedra* [Gelechia] *gossypiella*) was discovered in Montserrat and St. Kitts. The Entomologist visited these islands for the purpose of assisting the local agricultural officers in planning for the control of this pest. Antigua and Nevis were visited for the purpose of inspection, but the insect was not found there at that time.

Information with regard to the discovery of the pink bollworm in the West Indies and its subsequent spread and development as a pest of West Indian Sea Island cotton has been given from time to time in the *Agricultural News*.

MYCOLOGIST'S VISITS. Mr. W. Nowell, Mycologist on the staff of the Imperial Department, resigned his position in July 1920, to take up that of Assistant Director of Agriculture and Mycologist on the staff of the Trinidad Department of Agriculture.

Miss E. M Wakefield, of the Royal Botanic Gardens, Kew, England, was appointed Acting Mycologist from September 8, 1920, to March 27, 1921.

The Acting Mycologist visited Antigua from October 27 to November 7, and Dominica, November 9 to December 7, for

the purpose of general mycological investigations. Miss Wakefield also visited Trinidad in January 1921.

Remarks on Climate.

AMOUNT AND DISTRIBUTION OF RAINFALL.

GRENADA. The rains were late in commencing, with the result that the cacao crop was late, and likely to be a short one. The weather was favourable to ground provisions and corn. Total rainfall at Richmond hill for the year was 68·66 inches.

ST. VINCENT. The rainfall for the year at the Botanic Gardens amounted to 104·83 inches. No rain fell during April. The wettest month was October, when 21·56 inches fell. The heaviest continuous downpour was on October 24 and 25, when 9·80 inches fell.

DOMINICA. The rainfall for the year was 74·56 inches. The distribution on the whole was satisfactory.

MONTSERRAT.

Rainfall for Montserrat

1920.

January	...	5·21
February	...	3·69
March	...	3·67
April	...	nil
May	...	1·12
June	...	2·55
July	...	4·89
August	...	6·25
September	...	8·00
October	...	4·88
November	...	7·39
December	...	7 00
Total	...	54·66 inches.

Generally speaking a prolonged drought existed in this season at the very time copious rains were required for the development and success of the staple crop, cotton. A considerable proportion of the cotton crop was established early in March, and when it is considered that the ideal rainfall, speaking generally, is that 2, 4, 6 and 8 inches of rain should fall for the four months succeeding the date of planting, the short crop produced by this island in 1920, can be understood.

ANTIGUA. The average rainfall taken from seventy stations was 30·09 inches, this being the lowest recorded since the year 1875, when an average of only 28·78 inches was obtained.

ST. KITTS. The total rainfall for the year 1920 at the Experiment Station was 38·75 inches. Of this 21 inches fell in the last five months. The drought during the first six months seriously affected the cane crop, which will be below the average.

NEVIS. The rainfall for the year from January 1 to December 31, 1920, was 38·18 inches, which is 0·04 inch less than that of last year.

Rainfall for the quarter is as follows :—

Quarter ending	March	31	7·82	inches
„ „	June	30	3·46	„
„ „	September	30	12·43	„
„ „	December	31	14·47	„

BRITISH VIRGIN ISLANDS. The rainfall for the year at the Experiment Station was 42·11 inches, as compared with 52·55 inches for the previous year. This shows a decrease of over 10 inches for the year under report. Spells of drought of great severity were experienced in March and April, and during June and July.

ABNORMAL OCCURRENCES (PERIODS OF DROUGHT, WET WEATHER, WIND)

DOMINICA. During April the weather was very dry, with a total rainfall of only 22 inches. This is the lowest rainfall recorded at the gardens for any month since the records were first kept twenty-eight years ago. Heavy squalls were experienced on the morning of November 1, and a gale of almost hurricane force blew and lasted several hours.

MONTSERRAT. It is interesting to record that in the month of April 1920, only two recording stations in the island out of a total of twenty-three stations so far as is known, measured any rain whatever, and at the two stations referred to it was quite small in amount, actually 8 and 12 parts, respectively. In spite of this remarkable drought in April, it was evident, judging from the appearance of the young cotton at the end of the month, that had ample rains fallen in the months of May and June, a normal crop would probably have been assured. As it happened, the weather, so far as rainfall is concerned, was much more nearly to the ideal for the development of the second crop, and it is practically certain that for the first time on record the second crop of cotton was larger in total amount than the first crop.

ANTIGUA. *Drought.* From the months of January to July an average amount of not exceeding 3·00 inches was recorded. From August to November the heaviest rains were experienced during the month of October, when 5·41 inches were recorded.

Wind. From January to August fairly strong winds were experienced. From September to November the force of the wind was normal. The highest speed experienced during the year was 375 miles in twenty-four hours on June 22, 1920.

ST. KITTS Period of severe drought for first seven months, fair rainfall during the latter part of year. No disturbances of any kind from wind or rain occurred during the year.

NEVIS. The early part of the year was very dry, and the dry period was worst between April and June. Toward the

latter part of the year the weather was much moister. The year, on the whole, was calm, and no damage was done to the crop from high winds.

BRITISH VIRGIN ISLANDS. One earthquake shock of slight severity was recorded on August 2. Torrential downpour of 3·80 inches recorded on May 27. High winds experienced in January and October.

INFLUENCE OF WEATHER ON CROPS.

ST. VINCENT. The heavy rainfall in October and November caused considerable damage to cotton bolls. They were heavily attacked by soft rot.

DOMINICA. The weather has been very favourable for all crops particularly limes, which have yielded a heavy crop.

MONTSERRAT. Not only had the abnormally dry period from March to July 1920 a deleterious effect on staple crops, cotton and limes, but during the whole of this period practically no vegetable crops could be planted, and much hardship resulted through the scarcity of vegetables, especially sweet potatoes, until about the month of December 1920. Fairly good crops are being reaped late in the year as the result of the satisfactory rains from July to December.

ST. KITTS. The weather has been responsible for a considerable shortage in the sugar crop, and also in the planting of ground provisions.

NEVIS. On account of the dry weather during the early part of the year great difficulty was experienced in getting the crops established, and growth was slow until September, when the rains came, from which time on the crops all made rapid progress.

BRITISH VIRGIN ISLANDS. Great difficulty was experienced in establishing cotton fields on account of the long spells of drought experienced during the planting season. Heavy rains in October and November caused some damage to cotton fields by the rotting of all bolls on the lower branches of plants.

PART 1. INSECT PESTS OF ECONOMIC PLANTS.

Sugar-Cane.

MOTH BORER (*Diatraea saccharalis*, Fabr).

GRENADA. Generally distributed. Locally severe.

ST. VINCENT. Present in all cane fields.

ST. LUCIA. Fairly general but not severe.

MONTSERRAT. Continues to be troublesome in certain localities, and is undoubtedly responsible for considerable loss on estates in the centre of the island.

ANTIGUA. Present in all cane fields throughout the island, especially in fields containing young sprouts. About 40 per cent.

of mature canes have been found to be infected with moth borer on one estate.

ST. KITTS. Generally attacking sugar-canes, but more in advanced stage. Not a large number of what is known locally as 'Dead Hearts' in young canes. The pest cannot be said to have increased.

NEVIS. The moth borer occurred throughout the island causing an appreciable amount of damage in both ratoon and plant cane fields. On nearly all the estates the cuttings are put in a lime solution, which the planters claim destroys the grubs in the cuttings, but it would appear that the death of grubs is caused from drowning rather than anything else.

BRITISH VIRGIN ISLAND. Generally present in cane fields, especially in old ratoons.

WEEVIL BORER (*Sphenophorus sericeus*, Oliv.).

GRENADA. Not reported.

ST. VINCENT. Noticed on several occasions during the season.

ST. LUCIA. Generally present but not serious.

ANTIGUA. Present in most cane fields. Not generally regarded as a very serious pest, although in fields of young sprouts, some plants have been utterly destroyed by it.

ST KITTS. No occurrence of this pest as far as effecting any serious loss.

NEVIS. The adult was found in hedges in the neighbourhood of cane fields, but no damage is observed to have been done by the grub.

BRITISH VIRGIN ISLANDS. Not observed.

ROOT BORERS (*Diaprepes abbreviatus*, L.).

ST. LUCIA. Generally present but not serious.

MONTSERRAT. This insect is undoubtedly very rare in the island, only occasional specimens of the weevil being seen.

ANTIGUA. Not observed since 1917.

ST. KITTS. Root borers are prevalent in some districts, but there has been no special instance reported of serious loss from them.

NEVIS. Adult less prevalent than in the past; no damage observed to have been done by grub.

BRITISH VIRGIN ISLANDS. Found in ratoon canes but no great damage observed to have been done by the larvae.

Diaprepes famelicus, var. (*Exthophthalmus esuriens*).

ST. LUCIA Found only in dead canes.

MONTSERRAT. Adult specimens are seldom seen in numbers in sugar-cane fields, but it is not known to what extent the grubs of the insect are infesting the fields.

ANTIGUA Adults of this pest were quite common in cane fields during the month of April and May. They were observed

on the plants of the Wild Lord Lavington (*Leonurus Sibiricus* and also on Cattle tongue (*Pluchea odorata*). Larvae were also found in the soil not doing any noticeable damage.

ST. KITTS. This pest is of general occurrence, and the beetles can be found on cotton plants and in the heart of cane in large numbers. There has, however, been no actual epidemic or serious loss from them during the year. From personal observations it appears that, under good agricultural conditions, the canes are able to resist the attacks of these root borers, but where the canes are poor for want of manure, etc., they are liable to almost total destruction from these pests. In the opinion of the Agricultural Superintendent, the control of these root borers lies in better agricultural conditions.

NEVIS. Exophthalmus adult observed throughout the island, on peas, cotton and lime, but no damage is observed to be done by the grub.

BRITISH VIRGIN ISLANDS. The beetles were observed in fields of young canes,

CANE FLY (*Saccharosydne saccharivora*, West.).

BRITISH VIRGIN ISLANDS. Observed in fields of canes but not apparently doing much serious damage.

WHITE ANTS OR TERMITES

ANTIGUA. Nests found in cane fields throughout the island, but very little damage appears to have been done by the insects

ST. KITTS. No report of any damage done during the year.

NEVIS. Not observed attacking the sugar-cane.

BRITISH VIRGIN ISLANDS. Generally prevalent ; not a serious pest of cane.

HARD BACK GRUBS (*Lachnosterna* spp.).

ANTIGUA. *Lachnosterna antiguae* occurs chiefly in the north-eastern and central plains of the island, heavy infestations being recorded in the central plains. This insect does not occur in the southern and south-western districts. The grubs are responsible for a certain amount of damage to canes, especially in the fields of young sprouts.

Grubs of *Ligyrus tumulosus* are also to be found in fields which have been manured with pen manure. No damage to canes has been attributed to this insect.

ST. KITTS. *Ligyrus tumulosus*, both adult and grub, found in fields, especially where well manured. No damage seems to be done by them.

NEVIS *Ligyrus tumulosus*. Grub observed in rotting green manure, more around the edges of the heap than in the centre. Adult observed in the field during preparation. The insect appeared to be just about to emerge. This was

during the months of March and April. No damage has been observed to be done to the crop by this insect.

OTHER INSECTS ATTACKING SUGAR-CANE.

GRENADA. Froghopper (*Tomaspis saccaharina*). Locally severe in St. Johns and St, Andrews. At a late stage in the attack, froghoppers were observed to be heavily parasitized by a fungus.

ST. LUCIA. Mealy-bug common in cane fields, especially on unmanured land. Various grasshoppers do minor damage to young cane foliage. There is also a small beetle which does a fair amount of damage to young cane.

ANTIGUA. Grasshoppers are sometimes known to eat the leaves of young canes.

ST. KITTS. Grasshoppers are a serious troub'e at times to young cane plants.

NEVIS The grasshopper did a great deal of damage to the young canes. This insect is found feeding on the cane leaves all through the year, but the damage to advanced fields is not considered so bad. The pest has increased during the past year, This is no doubt due to damage done to poultry by the mongoose, as both fowls and turkeys are particularly fond of the grasshoppers

Mealy-bug was observed this year throughout the island on both plants and ratoons.

BRITISH VIRGIN ISLANDS. Mealy-bug common in ratoon fields, especially during the drier months.

COTTON.

COTTON WORM. (*Alabama argillacea*, Hubn.).

GRENADA. Not observed.

ST. VINCENT. A few noticed during the season. No serious infestation occurred.

ST. LUCIA. Fairly numerous but controlled by frequent applications of lime and Paris green.

MONTSERRAT. Light attacks of worms were experienced on certain areas in the month of August, but severe attackt were, as usual, comparatively late in the year, and is required persistent dusting with poison on certain areas in the months of September and October to keep them under control. It is of interest to record that very few of the peasant growers ever attempt the control of the cotton worm, and their crops are seldom severely damaged by the pest. Defoliation of the peasant s crop through attacks of cotton worm was more common than usual.

Certain localities in the island as a rule escape infestation by cotton worm, though experience in this season showed that a district that had been immune to attacks of worm for many years had a rather severe infestation in the later months of the year.

ANTIGUA. Slight attacks of cotton worms were experienced throughout the island; no considerable loss was caused from them, hence very little dusting was performed.

ST. KITTS. This pest was prevalent during the past season, and large quantities of poison were used to control it. No actual damage was done to the plants.

NEVIS. The cotton worm was very servere in its attack during the year, but ample preparations were made for dealing with the pest, and practically no damage was done by it. The attack started as early as June, when the crop was very young, and lasted (with about fourteen days between attacks), until the middle of November, when the attack ceased. The pest, for about the first time, has been kept under control.

BRITISH VIRGIN ISLANDS. Attacks were not observed until late in the year. In November and December, severe attacks were experienced, which caused great damage in the cotton fields, entirely defoliating the plants.

A. BOLL WORM (*Heliothis obsoleta*, Hubn.), and

B. CORN WORM (*Laphygma frugiperda*, S. and A.).

GRENADA. Not observed.

ST. LUCIA. Not noticed on cotton.

MONTSERRAT. A few instances of bolls damaged by this pest were observed in the month of November, but as a rule it is extremely scarce, and is not regarded as a pest of any importance at the present time.

ANTIGUA. Slight attacks of the boll worm were experienced in the southern districts of the island but not causing very considerable damage.

The corn ear worm was not observed attacking plants during the year.

ST. KITTS. These pests have been seen but in rare instances, and no damage has been done by them.

NEVIS. *Heliothis*. This pest did a great deal of damage this year, chiefly in lands cleared of bush. The planters were advised to plant rows of corn in the cotton fields, as the pest seems to prefer the corn to cotton bolls.

BRITISH VIRGIN ISLANDS The corn ear worm was noticed in small quantities in cotton fields doing practically no damage.

COTTON STAINERS (*Dysdercus* spp.).

GRENADA. Fairly plentiful on Sea Island cotton, also generally distributed on Marie Galante.

ST. VINCENT. Generally present; increased considerably towards end of season.

ST. LUCIA. Present in fair numbers on both estates on which Sea Island cotton is grown, but kept under control.

MONTSERRAT. The earliest attack on cultivated fields occurred towards the end of August, and by the middle of October

the whole of this particular estate was infested. Other scattered areas were invaded early in September, and the pest was, as usual, generally prevalent towards the end of the year,—November and December. In cases of early development of the pest, no attempt was made to control it, the infected areas being on cotton lands planted on the share system. It is to be admitted, however, that practically no attempts are made by planters to control the early attacks of this pest. Generally speaking, the loss of crop due to cotton stainers was small.

ANTIGUA. Adults of *Dysdercus andreae* appeared in large number during the months of September and October onwards. Traps of cotton seed for their control were started.

ST. KITTS. Cotton stainers appeared late in the season They were more prevalent in northern districts where the cotton was planted early, appearing about November and December, when the cotton was nearly all reaped. The destruction of the native food-plants of this pest has been of value, and the work should be carried on.

NEVIS. This pest is not so plentiful since the campaign against it has been started. During the months of November and December (1920), when the usual attack of stainers was expected, they appeared in only certain localities, and few in number; later they appeared more generally but fewer, and damage from this pest is nil compared with past years.

BRITISH VIRGIN ISLANDS. Cotton stainers did not become noticeable before September, from which month they increased considerably.

BUSH BUGS (*Nezara viridula*, L. I., and others).

GRENADA. Generally distributed on all cotton.

ST. VINCENT. No serious attack; controlled by egg-parasites.

ST. LUCIA Usually found in cotton patches. No damage noticed from this pest.

MONTSERRAT. This insect, as a cotton pest, is generally ignored. Observations in the Experiment Station showed that adult insects of this pest were much more plentiful early in the year, in the months of June and July, than later in the year, and this would seem to confirm the observation in St. Vincent where egg-parasitism increases towards the end of the year.

ANTIGUA. Common in all cotton fields, and also pasture lands. They are sometimes held responsible for staining cotton.

ST. KITTS Seen in cotton fields but no damage observed.

NEVIS. Fairly plentiful this year. This pest in the past was not regarded as serious, but more damage has been done by it this year than by the cotton stainer. It occurred in nearly every cotton field, and plentifully on peas and beans and certain wild plants.

Noticed in most cotton fields.

BLACK SCALE (*Saissetia nigra*), and WHITE SCALE (*Hemichionaspis minor*).

GRENADA. Black scale not observed. White scale generally distributed; severe.

ST. VINCENT. Present in fair quantites towards the end of the season; did no serious harm.

ST. LUCIA. Both common on ratoon short-stapled cotton all over the island.

MONTSERRAT. Sporadic cases of attack on cotton and other groups of plants by black scale are noted but never to the extent to cause it to be regarded as a serious pest.

ANTIGUA. These were both observed, on old cotton plants but are not held responsible for any great damage,

ST. KITTS. Both the black and the white scales were observed, but plants were pulled off before any damage was done.

NEVIS. The black scale observed in many fields, but not considered a serious post. The white scale not observed since a close season has been established. It appears to attack the crop in a later stage than the black scale.

BRITISH VIRGIN ISLANDS. Both present in cotton patches.

FLOWER-BUD MAGGOT (*Contarinia gossypii* Felt).

MONTSERRAT. Damage resulting from this insect has not been heard or seen of for many years.

ANTIGUA. Slight attacks were observed in the southern districts during the month of October.

ST. KITTS. Does not occur in St. Kitts

NEVIS. Not observed.

BRITSH VIRGIN ISLANDS. Not recorded during the year.

LEAF BLISTER-MITE (*Eriophyes gossypii* Banks).

GRENADA. Generally distributed and fairly scarce on Marie Galante cotton in Carriacou, Grenada and Isle de Rhonde.

ST. VINCENT. Present on secondary growth at the end of the season; caused no injury to crop.

ST. LUCIA. Persistent efforts to destroy this pest in Sea Island cotton trial fields keep it under control. Otherwise found in cotton bush all through the island.

MONTSERRAT. This pest was generally more prominent than for many years, in spite of the fact that the destruction of the old cotton crop early in 1920 was very efficiently performed. It was frequently suggested during the season, that the striking prominence of the pest was in some way associated with the particularly dry season in the early period of growth, and some importance must be attached to this circumstance

ANTIGUA. Common throughout the island. Owing to the large amount of wild cotton plants growing in uncultivated lands, the control of this mite was made very difficult.

ST. KITTS. Leaf blister-mite was very prevalent at the close of the season, but little damage was done to cotton plants. It was hoped that the close season for cotton would have almost eradicated this pest, but this has not been the case.

NEVIS. Not so plentiful as in the past. This is due to the establishment of a close season.

BRITISH VIRGIN ISLANDS. Found wherever cotton is grown, and is a serious menace to late planting. Early planted fields are less susceptible to infestation

OTHER INSECTS ATTACKING COTTON.

ST. VINCENT. Red spider on cotton at the Experiment Station. Aphis is somewhat abundant in the windward district.

MONTSERRAT. On November 5, 1920, the pink bollworm of cotton (*Gelechia gossypiella*) was discovered in the island in considerable numbers on the area where it was found. The early observations indicated that the pest was confined to the neighbourhood of the port (Plymouth), but at the close of November and in December it was found to be distributed from the town to the extreme north of the island, only slightly towards the south, and to some extent towards the eastern or windward side of the island the latter district being relative free from it.

ANTIGUA. The red lady-bird beetle (*Cycloneda sanguinea*) was observed to be very common in cotton fields. Larvae of the lesser cotton worm (*Aletia luridula*) were found in cotton bolls, but are not held responsible for doing any great damage.

ST. KITTS. The pink bollworm of cotton (*Gelechia gossypiella*) was discovered in St. Kitts on November 15, at La Guérite Experiment Station, and later on the estates from the town of Basseterre to Cranstouns estate. Cockroaches have been observed cutting off the young plants soon after germination.

NEVIS. Lachnopus observed doing a fair amount of damage on a certain estate. A large black grass worm did a fair amount of damage to young cotton by feeding heartily on the leaves.

BRITISH VIRGIN ISLANDS. Cotton aphis was particularly prevalent during the dry months.

CACAO.

THRIPS (*Heliothrips rubrocinctus Giard*).

GRENADA. Generally distributed, and in some instances locally severe. Spraying with Bordeaux mixture and soap-nicotine has been carried out on several estates with success. Generally speaking, records show that this has been the mildest year for thrips since 1916. Spraying demostrations have been given to the peasants.

ST. VINCENT. No serious attacks.

ST. LUCIA. Severe, generally on lowlands and damp hillsides.

DOMINICA. Generally present in cacao cultivation. No bad effects reporded.

BEETLE (*Steirastoma depressum, L.*).

GRENADA. Observed principally on the western side of the Island.

ACROBAT ANT (*Cremastogaster brevispinosa*, Forel.).

GRENADA. Generally distributed and locally severe.

SCALE INSECTS AND MEALY-BUGS.

GRENADA. Generally distributed on cacao in close association with the Acrobat ant.

ST. LUCIA. Mealy-bugs often found on flower cushions, pods and leaves.

BRITISH VIRGIN ISLANDS Mealy-bugs occasionally met with in the few isolated cacao patches in the island.

OTHER INSECTS ATTACKING CACAO.

GRENADA. Termites (*Kalotermes balloui*) observed on the eastern side of the island. Locally severe. Further investigations regarding this pest are being made.

LIMES AND OTHER CITRUS.

SCALE INSECTS.

GRENADA. The following are generally distributed and are locally severe: *Lepidosaphes beckii, Chionaspis citri, Coccus viridis, Selenaspidus articulatus.*

ST. VINCENT. Citrus plants generally badly attacked.

ST. LUCIA. *Chionaspis citri* generally present, especially in dry and exposed situations. *Saissetia nigra* found in fields where okros have been grown. *Coccus viridis* generally present, severe in nursries. *Selenaspidus articulatus* generally present on lime leaves, apparently doing little damage. *Lepidosaphes beckii* generally distributed; severe, more especially where cultivation is poor.

DOMINICA. A severe attack of *Orthezia insignis* on lime trees occurred on the south side of the island towards the close of 1919, and continued more or less senere during 1920. The pest was also found on an estate on the leeward coast, and to some extent in the Lime Experiment Station. The pest is now confined to ths Soufrière district.

MONTSERRAT. There have been no striking epidemics of scale insects during the year, except that on restricted areas, the long drought from March to July 1920 resulted in considerable development of purple scale, with the accompanying dying back branches.

The green scale and Croton bug have been comparatively scarce for some years, consequently the trees have not been severely infested with black blight.

ANTIGUA. The following scale insects were observed: The purple scale (*Lepidosaphes beckii*), the Orange snow scale (*Chionaspis citri*), and the green scale (*Coccus viridis*,).

ST. KITTS. No lime cultivation to any extent in St. Kitts, but scale insects are found on all trees.

BRITISH VIRGIN ISLANDS. *Chionaspis citri* generally present, especially during spells of dry weather. Others found are *Lecanium hemisphericum, Saissetia nigra,* and *Coccus viridis.*

BARK BORER (*Leptostylus praemorsus*).

GRENADA. Not reported.

ST. LUCIA. Present in the drier districts, not severe, controlled.

DOMINICA. Occasionally met with.

ANTIGUA. Adults have been found in the southern parts of the islands. This pest is apparently on the increase.

TWIG BORER (*Elaphidion mite*).

No records of the occurrence of this pest during the year.

ROOT BORERS, ROOT GRUBS (*Diaprepes* spp.) and (*Exophthalmus* spp.).

ST. LUCIA. *Diaprepes abbreviatus*, var is fairly numerous, but damage to roots uncertain.

ANTIGUA. No observations made.

BRITISH VIRGIN ISLANDS. The larvae of (*Diaprepes abbreviatus var. spengleri*) common in lime fields. The adults noticed flying about and eating lime leaves.

OTHER INSECTS ATTACKING CITRUS.

ST. LUCIA. Weevil (*Neocyphus pudens*) found attacking lime in the Soufriére district.

SWEET POTATO.

SCARABEE (*Cryptorhynchus batatae*, Waterhouse).

ST. VINCENT. Found in overripe potatoes. No serious attack occurred.

ANTIGUA. Common on all peasant lands, especially where sweet potatoes are continually being grown. In some districts the entire crop is lost. Sweet potatoes grown in rotation are usually free from infection.

ST. KITTS Found in poor land but not in great abundance.

NEVIS In very few places was this pest observed, and its occurence is due chiefly to the crop being allowed to remain in the ground too long.

BRITISH VIRGIN ISLANDS. This insect is only noticed in over-ripe fields and is not considered a very serious pest at present.

CATERPILLARS (*Protoparce cingulata*, Fabr.) and others.

ST. LUCIA. Caterpillar attacks were serious during November and December.

ANTIGUA. Common throughout the island, and fields have been observed to have been entirely defoliated through this pest.

ST. KITTS. No record this year.

NEVIS. Protoparce observed in only a few places. Not considered a serious pest.

BRITISH VIRGIN ISLANDS. Very servere attack experienced, and much damage done to the crop during the month of October.

THRIPS.

ST. LUCIA. Present, not severe.

RED SPIDER (*Tetranychus telarius*, Linn.).

ST. VIVCENT. Found during the season. No serious attack occurred.

OTHER INSECTS ATTACKING SWEET POTATO.

ST. LUCIA. The common slug (*Veronicella occidentalis*) is a real pest in low wet lands, principally. Bush bugs generally distributed, but damage not severe.

DOMINICA. The 'Palute' (*Veronicella occidentalis*) eats the leaves of sweet potatoes. Always present to some extent.

GROUND NUTS,

GREEN BUG (*Edessa meditabunda*, F.) and others.

ST. VINCENT. Generally present.

MEALY BUG.

NEVIS. Observed in plot at Experiment Station, but not to a great extent.

BRITISH VIRGIN ISLANDS. Generally present.

LEAF-EATING CATERPILLARS.

ST. LUCIA. Generally present.

OTHER INSECTS ATTACKING GROUND NUTS.

No records during the year.

COCO-NUTS.

WEEVIL (*Rhyncophorous palmarum*, Linn.).

GRENADA. Observed in trees dying or dead from Red Ring disease, also destroying hearts of young coco-nut palms. Generally distributed, and noticed to be locally severe in one instance.

ST. VINCENT. Few instances noticed during the year.

ST. LUCIA. Rarely met with.

WHITE FLY (*Aleyrodicus cocois*, Curtis).

ST. VINCENT. Fairly common.

ST. LUCIA. Present, generally not serious.

DOMINICA. Occasionally found on young coco-nuts.

BRITISH VIRGIN ISLANDS. Noticed, but no serious damage done to trees.

SCALE INSECTS (*Aspidiotus destructor*, Sign.). and others.

GRENADA. Generally severe, more so during the dry season.

ST. VINCENT, Generally present.

ST. LUCIA. Fairly serious and general on young trees in dry situations, during dry spells, and in sandy soil along the coast. *Diaspis boisduvalii* also present in situations similar to those mentioned above, and fairly serious.

DOMINICA. Scale insects are occasionally met with on coco-nut palms throughout the island. The serious attack of *Aspidiotus destructor* reported from the Windward Coast last year is now under control.

ANTIGUA. Generally observed on the under surface of the leaves throughout the island, but apparently does little damage.

ST. KITTS. No large coco-nut cultivation in St. Kitts, but scale insects are found on all trees.

NEVIS. Aspidiotus observed throughout the island, but chiefly on the older leaves, and on younger leaves on plants growing under bad conditions. Also observed on bunches of nuts at Pinneys and other places.

BRITISH VIRGIN ISLANDS. Prevalent in all coco-nut-growing districts.

INDIAN CORN.

CORN EAR WORM (*Heliothis obsoleta*, Hubn.) and (*Laphygma frugiperda*, S. and A.).

GRENADA. Noticed in various localities in form of mild attacks.

ST. VINCENT. Generally present. Did no serious damage.

ST. LUCIA. Generally distributed. Particularly troublesome throughout the year all over the island.

ANTIGUA. Usually found in corn fields.

ST. KITTS. Very prevalent, and did much damage to young corn.

NEVIS. Very abundant throughout the island, causing a fair amount of damage.

BRITISH VIRGIN ISLANDS. Corn ear worm is generally present in corn fields.

HARD BACK GRUBS (*Lachnosterna* spp.)

ANTIGUA. Grubs of *Lachnosterna antiguae* are plentiful in some districts, often causing considerable damage.

ST KITTS. Not observed damaging corn.

NEVIS. Not observed attacking corn.

BRITISH VIRGIN ISLANDS. Grubs of *Lachnosterna* spp. noticed.

OTHER INSECTS ATTACKING INDIAN CORN.

ST. VINCENT. *Diatraea saccharalis* generally present.

ST. LUCIA. Grain weevils generally distributed. Attack both in the fields and in store.

MONTSERRAT. It is possible that the very young caterpillars of the worm *Prodenia* sp. can destroy young germinating corn. A plot of special corn from Bermuda was planted in the Experiment Station in September, and as the seedlings germinated, at less than four days from planting, they were found to be plentifully infested with small caterpillars, and were completely destroyed even before they had formed a stand. The habits of the corn ear worm would probably not account for the infestation by this pest at so early a stage.

ANTIGUA. Adults of *Tachytes argentipes* were observed on corn plants, apparently attracted by the inflorescence. Adults of *Tiphia parallela* were also found on corn plants during the year. The granary weevil is common when seed is stored.

ONIONS.

CATERPILLARS.

ANTIGUA. Common in onion fields. Collecting by hand for its control is adopted, and found to be the best method of control.

NEVIS. Observed in nursery beds but did no damage to general crop.

BRITISH VIRGIN ISLANDS. Onions in all districts suffered from attacks of caterpillars.

THRIPS (*Thrips tabaci*, Lind.).

ANTIGUA. Observed in fields during the year but apparently not on the increase.

BRITISH VIRGIN ISLANDS. Common in onion fields.

OTHER INSECTS ATTACKING ONIONS.

ANTIGUA. Grubs of *Lachnosterna antiguae* have been found in Antigua onion fields apparently attacking the roots of the plants, but no great damage has been recorded.

YAMS.

SCALE INSECTS (*Aspidiotus hartii.*).

GRENADA. Yams were observed to be attacked severely in two parishes. Specimens were forwarded to the Imperial Commissioner of Agriculture.

ST. VINCENT. Fairly common.

ST. LUCIA. Generally distributed, fairly serious.

ANTIGUA. Usually found, but apparently does very little damage.

ST. KITTS. Attacks stored yams.

OTHER INSECTS ATTACKING YAMS.

ST. LUCIA. Slugs are troublesome during early growth.

ANTIGUA. Grubs of *Lachnosterna antiguae* have been found in a field of yams, but apparently very little damage was done by them.

GREEN DRESSINGS—BEANS AND PEAS.

LEAF-EATING CATERPILLARS.

GRENADA. Severe attacks of *Anticarsia gemmatalis* were observed on *Canavalia ensiformis.*

MONTSERRAT. Were not prominent on green dressing crops during the year.

ANTIGUA. Green dressings of white velvet bean, and the fleshy pod bean have been attacked, often causing complete defoliation.

ST. KITTS. These were prevalent on all kinds of green dressings, owing chiefly to the very dry season.

BRITISH VIRGIN ISLANDS. Caterpillars were noticed attacking *Canavalia ensiformis*, pigeon peas, and black-eye peas, but no great damage was done.

BUSH BUGS (*Nezara viridula*).

ST. VINCENT. Generally present.

ANTIGUA. These were observed to be very common, but are not held responsible for doing much damage.

NEVIS. Nezara very abundant on peas and beans, causing a great deal of damage by sucking the pods.

BRITISH VIRGIN ISLANDS. Noticed in fields of black-eye peas and pigeon peas

OTHER INSECTS ATTACKING THESE CROPS.

ST. VINCENT. *Ballovia* sp. found attacking pods of pigeon peas and cowpeas.

ST. KITTS. Grasshoppers at times cut off the young plants.

PLANTAINS AND BANANAS.

BLACK WEEVIL BORER (*Cosmopolites sordidus.*)

ST. LUCIA. Generally distributed and on the increase. Damage is more apparent during the dry season. The spread of

this insect is materially aided by neglect in examining suckers carefully, before planting new gardens.

DOMINICA. Present, but no serious damage reported.

WEEVIL BORER (*Metamasius sericeus*, Oliv.).

No records during the year.

LARGE BLACK HARD BACK BORER (*Tomarus bituberculatus*, Beaud.).

ST LUCIA. Generally distributed and serious, particularly during spring and the beginning of the wet season. This pest, besides being able to fly fairly long distances after nightfall, is spread in very much the same way as the black weevil borer.

TANNIAS, DASHEENS, EDDOES.

BANANA BORER (*Tomarus bituberculatus*, Beaud.)

ST. LUCIA. Generally distributed and serious, particularly during spring and the beginning of the wet sea-son. Retards the growth and development of the plant, and sometimes destroys it completely.

LACEWING BUG.

ST. LUCIA. Generally distributed, not serious.

GENERAL REMARKS.

MISCELLANEOUS INSECTS NOT OTHERWISE PROVIDED FOR.

GRENADA. An unidentified beetle, attacking pine-apples, specimens of which were forwarded to the Imperial Commissioner of Agriculture, was observed as a serious pest in one locality. Loss of the crown of the pine was the injury, also puncturing and gumming of the fruit.

ST. VINCENT. Mole cricket, a common pest of garden vegetables also attacks Indian corn and cotton.

ST. LUCIA. The mole cricket (*Gryllotalpa didactyla*) is a common pest of garden vegetable crops, especially cabbage, lettuce, tomatoes, etc, and is difficult to control. Lawns also suffer materially from the ravages of this insect.

ANTIGUA. The larvae and adults of *Mallodon maxillosum* were found in the interior of Sandbox tree. (*Hura crepitans*), several trees dying in consequence. Adults of *Phileurus valgus* were also found.

ST. KITTS. A large borer does great damage to White Cedar trees throughout the island.

NEVIS. The grasshopper has been a source of damage to young canes. Lachnopus for the past three or four years has appeared as a pest of cotton.

BRITISH VIRGIN ISLANDS. *Calpodes ethlius* attacks canna. *Batocera rubus* attacks papaw and wild fig.

NATURAL ENEMIES OF INJURIOUS INSECTS—PARASITIC AND PREDACEOUS INSECTS.

GRENADA. Lady bird beetles were generally distributed.

ST. LUCIA. Jack Spaniards are fairly well distributed in the Soufrière district.

ANTIGUA. Soil grubs of *Lachnosterna antiguae* were observed to be parasitized by *Tiphia parallela.*

The wild bee or Jack Spaniard was observed in the northern and southern districts of the island.

Adults of *Campsomeris dorsata, Tachytes argentipes,* and *Sphecidae* were observed in the island during the year.

ST. KITTS. Jack Spaniards help in keeping the cotton worm in check.

NEVIS. Chalcis as a parasite of the cotton worm was observed during the month of November.

The fiery ground beetle was observed feeding on the cotton worm in the New Road district.

The Jack Spaniard was fairly plentiful in all the cotton fields. They appear to leave the dry districts during the hot seasons, and the remaining few become less aggressive.

BRITISH VIRGIN ISLANDS. Jack Spaniards are becoming more common in the Virgin Islands again. In Tortola, quite a few nests have appeared.

OTHER REMARKS.

ST. KITTS. Insects generally have been prevalent during the year, the results of the very dry weather.

NEVIS The cotton worm was severe in its attacks this season but it was kept in check by the use of insecticides. There is a marked reduction in the number of cotton stainers, and the damage done to the crop by this pest is becoming less and less. Nezara, however, seems to be on the increase.

On the whole, the damage done to crops this year has not been great.

BRITISH VIRGIN ISLANDS. Insect pests, on the whole, were only serious during the last three months of 1920, especially in November. Curly leaf disease of cotton was noticed during the wet months in Tortola.

PART II.—DISEASES OF ECONOMIC PLANTS.

CACAO.

ROOT DISEASES (*Rosellinia* spp.)

GRENADA. Local attacks have been observed. Copperas has been used as a control.

ST. LUCIA. Well distributed and severe in many plantations in the Soufrière district. Control measures are persistent in all diseased plantations.

CANKER. (*Phytophthora Faberi*, Maub.).

GRENADA. Generally distributed and, in some instances, locally severe. Kept largely under control by tree surgery and the application of antiseptics.

ST. LUCIA. generally severe and distributed throughout the island. Improved methods of cultivation keep it under control on the larger plantations.

DOMINICA. Fairly common throughout the island at all times. A few severe cases noticed on estates on the Leeward Coast.

BLACK ROT OF PODS (*Phytophthora Faberi*, Maub.).

GRENADA. Not reported.

ST. LUCIA. Met with in plantations generally during heavy wet season. Was not so apparent this year. Control measures are undertaken in the larger plantations, and are being gradually adopted among the peasantry.

DOMINICA. Always present particularly on delicate varieties of cacao suffering from canker.

BROWN ROT OF PODS *Diplodia Theobromae*, Pat.).

GRENADA. Generally distributed and locally severe. Bordeaux nicotine used for spraying thrips serves to control this disease as well.

ST. LUCIA Present generally ; not serious this season.

DOMINICA. No serious cases reported or observed.

DIE BACK AND STEM DISEASE (*Diplodia Theobromae*).

GRENADA. Local, not severe.

ST. LUCIA. Generally bad, more serious on exposed situations

DOMINICA. Cacao fields are rarely found entirely free from this disease. Most troublesome on wind-swept land.

PINK DISEASE (*Corticium salmonicolor*, B and Br.).

GRENADA. Not reported.

THREAD BLIGHTS (*Corticium*, sp., etc.).

GRENADA. Not reported.

ST. LUCIA. Present in small plantations adjoining heavy forests

HORSE HAIR BLIGHT (*Marasmius equicrinus*, Mull, Blanc).

GRENADA. Observed in the highlands. Not observed.

COCO-NUTS.

BUD ROT (*Phytophthora palmivora*. Butl, etc.),

GRENADA, Not reported.

ST. LUCIA. Distributed to a limited extent. Few cases were reported during the year.

NEVIS. Occurred sporadically during the year in one plantation

BRITISH VIRGIN ISLANDS. Not noticed.

RED RING DISEASE (*Aphelenchus cocophilus*, Cobb).

GRENADA. Generally distributed and locally severe. prevention methods are in many instances being adopted to check its spread. Successful experiments were carried out at Westerhall for the destruction of diseased trees in the same form as charcoal is burnt.

ST. LUCIA. No cases reported as yet.

LEAF BLIGHT (*Pestalozzia palmarum*, Cke.).

GRENADA. Not reported.

ST. LUCIA. Present, not serious.

INDIAN CORN (see *Agric. News* XIV, 78).

RUSTS Red or Brown, (*Puccinia sorghi*, Schw.) (*P. maydis*, Bereng).

GRENADA. Not reported.

ST. VINCENT. Present, causing no serious injury.

ST. LUCIA. Brown rust is fairly common.

ANTIGUA. Generally found in maize fields.

ST. KITTS. Nil.

NEVIS. Occurred generally throughout the island, but chiefly on old plants.

BRITISH VIRGIN ISLANDS. Fairly common but not a serious disease.

SMUT (*Usti'ago Zeae*, (Beckm.) Ung).

GRENADA. Observed, not severe.

ST. VINCENT. Generally fairly common.

ANTIGUA. A few cases observed during the year.

ST. KITTS. Instances are observed but not to a great extent.

NEVIS. Occurred in a few places but not to a great extent.

BRITISH VIRGIN ISLANDS Not serious.

ROOT DISEASE.

ANTIGUA. Slight infestations found when grown with cane.

ST KITTS. Not observed.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS Isolated instances observed.

IMPHEE AND GUINEA CORN.

RUSTS (*Puccinia purpurea*, Cke.).

NEVIS. Of general occurrence when crop is ripening.

SMUT. *Agric. News*, XIII, 316 (*Sphacelotheca sorghi*, I. K. Clinton).

GRENADA. Not reported,

NEVIS Not observed.

ROOT DISEASE.

GRENADA Not reported,

Cotton.

SOFT ROT OF BOLLS (*Phytophthora sp.*).

GRENADA. Not reported.

ST. VINCENT. Common in October and November; caused a fair amount of damage.

MONTSERRAT. Found to be fairly plentiful in the showery month of September 1920, and is always responsible for the loss of a proportion of bolls in showery damp weather.

ST KITTS. Observed at the end of the season during wet weather

NEVIS, Not observed,

WEST INDIAN LEAF MILDEW (*Ovulariopsis gossypii*, Wakf.).

GRENADA. Not reported.

ST. VINCENT. Common at the end of the season.

ST. LUCIA. Prevalent during the wet November month.

MONTSERRAT. This was particulary evident on the heavier soils of the island during the third and fourth months of the crops' development (May and June), and it appeared in some way to be generally associated with the disease known as rust. In no previous season had there been such an amount of defoliation resulting from a combination of these troubles, but this was not evident on the lighter sandy soils of the island. The response to the rains in the later part of the year was very much less evident on the areas that had been partly defoliated in this way, on the first growth.

ANTIGUA. Generally found on plants towards the end of the crop.

ST. KITTS. Appeared at the end of the cotton season but did no damage.

NEVIS. Of general occurrence throughout the island. Not considered serious, as it generally occurs in fields that are ripening, and towards the end of the season.

BRITISH VIRGIN ISLANDS Present.

BACTERIAL BOLL DISEASE (external) (*Bacterium malvacearum*, E. F. S.)

ST. KITTS. Not observed.

NEVIS. Of more general occurrence than in the past.

BRITISH VIRGIN ISLANDS. Of rare occurrence during the season.

ANGULAR LEAF SPOT (*Bacterium malvacearum*).

GRENADA. Not reported.

ST. VINCENT. Generally present.

ST. LUCIA. Present to a limited extent.

MONTSERRAT. Our type of cotton is fairly immune to the disease associated with *Bacterium malvacearum*.

ST. KITTS. Observed to a slight extent, but not dangerous.

NEVIS. Of general occurrence throughout the island in fields that are ripening.

INTERNAL BOLL DISEASE (*Nematospora coryli*, Pegl., *Nematospora* sp., *Eremothecium cymbalariae*, Borzi, etc.).

GRENADA. Not reported.

ST. VINCENT. Common towards the end of the season.

MONTSERRAT. As usual associated with the attacks of green bug and cotton stainers.

ANTIUGA. Found throughout the island.

ST. KITTS. There has not been much loss from internal boll disease, as the loss from pink bollworm has taken its place.

NEVIS. Not so plentiful as in the past, but still occurst o a fairly great extent.

BRITISH VIRGIN ISLANDS. Generally distributed and did serious damage in wet months.

OTHER DISEASE OF COTTON OR GENERAL REMARKS.

ST. KITTS. The cotton crop has suffered early from lack of rain. The later planted fields would have yielded well, but the presence of pink bollworm will lesson the return.

NEVIS. A fair number of 'chilled' bolls was observed during the damp season.

BRITISH VIRGIN ISLANDS. Owing to lack of proper cultural treatment many cotton fields yielded poorly. Heavy rains in October and November caused the decaying of the majority of bolls on lower branches of cotton plants.

GROUND NUTS.

ROOT DISEASE (*Sclerotium Rolfsii*, Sacc.).

GRENADA. Not reported.

NEVIS. Not observed.

LEAF RUST (*Uredo arachidis*, Lag.).

GRENADA. Not reported.

ST. VINCENT. Generally present.

ST. LUCIA. Generally distributed, especially on wet lands.

ST. KITTS. Nil.

NEVIS. Occurred in the plot at the Experiment Station, but not to any great extent.

LIMES AND OTHER CITRUS PLANTS.

BLACK ROOT DISEASE (*Rosellinia* spp.).

GRENADA. Not reported.

ST. LUCIA. Appears on limes supplied to vacancies in cacao plantations caused by same disease in cacao.

DOMINICA. *Rosellinia bunodes* is fairly common on lime trees in newly cleared forest lands. *Rosellinia pepo* has been found

on one estate only. Both diseases can be controlled by burning diseased trees, and isolating contacts.

RED ROOT DISEASE (*Sphaerostilbe* sp.).

GRENADA. Not reported.

DOMINICA. Trees suffering from Red root disease (*Sphaerostilbe* sp.) were observed on two adjoining estates on the Leeward Coast during the year. Red root disease in Dominica appears to be confined to these two estates.

UNIDENTIFIED ROOT OR COLLAR DISEASES.

GRENADA. Generally distributed and locally severe.

DOMINICA. Collar rot on lime trees has been giving a good deal of trouble during the year. The disease can be treated in the early stages with good results by painting the diseased parts with lime and sulphur solution. Collar rot on orange trees was noticed on one estate only.

DIE-BACK

GRENADA. Generally found on trees infested with scale insects. Generally severe.

ST. LUCIA. Noticeable on low badly drained heavy lands.

DOMINICA. Commonly met with on estates where limes are grown on shallow or wind-swept land. Lack of sufficient humus in the soil and bad drainage contribute to the cause.

SEEDLING DISEASES.

GRENADA. 'Damping off' observed at the Botanic Station.

ST. LUCIA. 'Damping off' disease very prevalent during wet season in damp situations.

DOMINICA 'Damping off' of seedling lime trees is easily controlled by dusting the leaves, on the first appearance of the disease, with equal parts of lime and sulphur.

MONTSERRAT. Lime seedlings are invariably attacked by the mildew described in the Annual Report on the Montserrat Botanic Station for 1918-19, but Bordeaux mixture is found to be an effective remedy or preventive.

OTHER DISEASES OF LIME OR GENERAL REMARKS.

ANTIGUA. The lime cultivations in certain districts of the island have decidedly improved during the year under review, attention being especially given to the manuring of trees with pen manure and the cutting of all deadwood. Plants of Gliricidia were planted in the effort to established wind-breaks, but unfortunately, owing to drought, very few plants established themselves.

SUGAR-CANE.

ROOT DISEASE (*Marasmius Sacchari*, Wakker) and allied species.

GRENADA Not reported.

ST. VINCENT. Fairly common

ST. LUCIA Generally severe, particularly in the Bourbon variety.

ANTIGUA. Common throughout the island, especially in ratoon cane fields, and fields badly drained.

ST. KITTS. This disease is fairly prevalent throughout the island but only does damage where bad agricultural conditions are present.

NEVIS. Occurred throughout the island but not to any great extent.

BRITISH VIRGIN ISLANDS. Not generally present throughout the Presidency.

RIND FUNGUS (*Melanconium Sacchari*, Massee.).

GRENADA. Not reported.

ST. VINCENT. Common on over-ripe canes.

ST. LUCIA. General, particulary on wet lands.

ANTIGUA. Found throughout the island.

ST. KITTS. Not observed.

NEVIS. Observed in a few fields during reaping time.

RED ROT DISEASE (*Colletotrichum falcatum*, Went.).

GRENADA. Not reported.

ST. KITTS. Not observed.

NEVIS. Not observed.

PINE-APPLE DISEASE (*Thielaviopsis paradoxa*, von Hohn.).

GRENADA. Not reported.

ST. VINCENT. Noticed on cane cuttings.

ST. LUCIA. Present, not serious.

ANTIGUA. A few observed.

ST. KITTS. Not observed.

NEVIS. Not observed.

OTHER DISEASES OF SUGAR-CANE, OR GENERAL REMARKS.

ST. KITTS. There has been no epidemic of sugar-cane diseases during the year, and the recovery of the canes after the drought proved that they were in a healthy condition.

NEVIS. The cane crop on the whole, suffered from no serious fungoid diseases during the year.

SWEET POTATOES.

WHITE RUST (*Albugo* (*Cystopus*) *ipomeae panduranae* (Schw.) Sw.)

GRENADA. Not reported.

NEVIS. Not observed.

OTHER DISEASES, OR GENERAL REMRAKS.

NEVIS. This crop has been particularly healthy during the year.

BRITISH VIRGIN ISLANDS. A form of root disease observed in fields of English potatoes, and did some amount of damage to crop.

Bananas and Plantains.

Marasmius rot (*Marasmius stenophyllus*, Mont. *semiustus*, Mass.)

GRENADA. Not reported.

ST. LUCIA. Generally distributed and severe.

DOMINICA. Not known.

Yams.

Tuber diseases.

GRENADA. Not reported.

ANTIGUA. Not observed.

ST KITTS. Not observed.

NEVIS. Not observed

Wilt diseases.

GRENADA. Reported in association with *Aspidiotus Hartii.*

ANTIGUA. Not observed.

ST. KITTS. Nil.

NEVIS. Not observed.

Onions.

Bacterial rot.

GRENADA. Not reported.

DOMINICA Present, but not causing any damage.

ANTIGUA. Very little of this disease observed during the year.

ST. KITTS. Not observed.

NEVIS. Not observed.

BRITISH VIRGIN ISLANDS. Present in Virgin Islands.

Fungi Parasitic on Insects.

On scale insects.

GRENADA. *Cephalosporium lecanii* generally distributed.

BRITISH VIRGIN ISLANDS. Red-headed and shield-scale fungus seen during the year.

ST. LUCIA. The four common species occurred as usual.

DOMINICA. Fungus parasites, particularly the red-headed fungus (*Sphaerostilbe coccophila*), continue to do excellent work, in controlling attacks of scale insects.

ANTIGUA None observed.

ST. KITTS. None observed.

BRITISH VIRGIN ISLANDS. Red-headed fungus fairly common.

On any other insect.

GRENADA. Not reported.

ST. KITTS. None observed.

NEVIS. Not observed.

Phanerogamic Parasites.

LOVE VINE (*Cuscuta* sp).

GRENADA Generally distributed and locally severe. Shows tendency to increase.

ST. VINCENT. Common on bushes and estate land.

ST. LUCIA. Locally severe on wild as well as cultivated plants. Attempts to destroy it are generally made with more or less success. Among cultivated plants, hedges suffer most.

DOMINICA. Not plentiful.

MONTSERRAT. There are periods when the love vine is very prominent, but it appears to be attacked by a fungus or some controlling agent that turns it a brown colour, and it eventually dies.

ANTIGUA. A few cases observed in the island.

ST. KITTS. This pest is increasing on wild plants in villages, but does not attack cultivated plants.

NEVIS. Has increased especially on hedges.

BRITISH VIRGIN ISLANDS Contiuues to increase, and is destructive to hedges. Is also known to attack cotton, pigeon peas, cassava, and many wild plants.

MISTLETOE (*Dendropemon* sp.).

GRENADA. Generally distributed and locally severe on cacao.

ST. LUCIA. Generally troublesome on limes and cacao, but receiving attention generally.

DOMINICA. Very common on cacao trees in one district. Occasionally met with elsewhere in the island, but not to any great extent.

ST. KITTS. Not observed.

NEVIS. Generally observed.

BRITISH VIRGIN ISLANDS. Common on pear trees.

REMARKS ON ANY OTHER PLANT DISEASES.

ST. VINCENT. Imported tomato varieties generally affected by wilt diseases (*Bacterim solanaecarum*, E. F. S.

ST. LUCIA. Rosellinia root disease was locally present on avocado pear.

DOMINICA. Two diseases found on the leaves of French beans (*Phaseolus vulgaris*) were identified as Rust (*Uromyces appendiculatus* Lnk.) and leaf spot (*Cercospora cruenta* Sacc) A Fungus (*Mycophaerella brassicaecola*) together with a bacterial rot did considerable damage to cabbages planted on a fairly large scale on one estate in a wet district.

ST. KITTS. What is known locally as 'Old man's beard' *Tillandsia* sp.) is a great pest on certain trees, and is widely distributed.

NEVIS. None.

SUMMARY OF DISTRIBUTION.

The following table is intended to show the status and distribution of the pests and diseases affecting West Indian crops during 1920. It has been prepared from the reports which have been used in the compilation of the notes given in the preceding pages The following letters and signs are used as indicated, for brevity and graphic representation.

g = generally distributed.
G = generally distributed, severe.
l = local.
L = locally severe.
gL = generally present, locally severe.
r = occurred during year.
? = of doubtful occurrence.
– = not known to occur in the island.
o = no record during the year.
Blank space. Crop not grown in island, or of no importance.

INSECT PESTS.

	Grenada.	St. Vincent.	St. Lucia.	Dominica.	Montserrat.	Antigua.	St. Kitts.	Nevis.	Virgin Islands.
BANANAS AND PLANTAINS.									
Black Weevil Borer	o	o	G	r					
Brown Weevil Borer	o	o	o	o					
Black Hard-back Borer	o	o	G	o					
Other Insects	o	o	o	o					
CACAO.									
Thrips	gL	o	G	gg					
Beetle	l	o	o	l					
Acrobat Ant	gL	o	o	o					
Mealy-Bugs	gg	o	r	o					
Termites	L	o	o	o					
COCO-NUTS.									
Weevil	gg	r	?	-		-		-	-
White Fly	o	r	gg	r		o		o	r
Scale Insects	G	gg	gg	r		r	r	r	r
Other Insects	o	o	o	o				o	o
CORN (INDIAN).									
Corn Ear Worm and Boll Worm	r	g	G		o	gg	o	G	gg
Hard Back Grubs	o	o	o		o	L	o	o	r
Grain Weevils	o	o	gg		o	r	o	o	o
Moth Borer of Sugar-cane ...		g	o		o		o	o	o
COTTON.									
Cotton Worm	o	r	gg		g	gg	G	G	G
Lesser Cotton Worm	o	o	o		o	r	o		o
Boll Worm and Corn Ear Worm	o	o	o		r	l	r	L	r
Pink Bollworm	-	-	-		l	-	l	-	-
Cotton Stainers	g	g	gg		g	G	l	g	g
Bush Bugs	gg	r	r		gg	gg	r	gg	gg
Scale Insects	G	r	gg	l	l	r	r	r	r
Flower-bud Maggot	-	-	-		o	r	o	o	o
Leaf-Blister Mite	gg	r	gg		gg	gg	gg	r	gg
Aphis	o	l	o		o	o	o	o	gg
Red Spider	o	l	o		o	o	o	o	o
Cockroaches	o	o	o		o	o	l	o	o
Lachnopus	o	o	o		o	o	o	l	o
Caterpillar	o	o	o		o	o	o	l	o

INSECT PESTS.—(*Continued.*)

	Grenada.	St. Vincent.	St. Lucia.	Dominica.	Montserrat.	Antigua.	St. Kitts.	Nevis.	Virgin Islands.
GREEN DRESSINGS.									
(Beans and Peas.)									
Leaf-eating Caterpillars ...	L	o				L	g	o	g
Bush Bugs	o	g				g	o	g	r
Grasshoppers	o	o				o	o	o	o
Ballovia	o	r				o	o	o	o
GROUND NUTS.									
Bush Bugs		g	o				o	o	o
Leaf-eating Caterpillars ...		o	o g				o	o	o
Mealy-Bug		o	o				o	r	g g
LIMES AND OTHER CITRUS TREES									
Scale Insects	g	g	g	L	L	g			g
Bush Borer	o	o	r	r	o	l			o o
Root Borers, Root Grubs ...	o	o	r	o	o	o			g
Orange Moth	-	-	-	L	-	-			- g
Green Weevil	o	o	r	o	o	o			o
ONIONS.									
Caterpillar Cutworms						g			g
Thrips						r			g g
Hard Back Grubs						r			o
SUGAR-CANE.									
Moth Borer	gL	g	g		l	g	g	g	g
Weevil Borer	o	r	g g		o	g g	o	r	o
Root Borer Diaprepes	o	o	g g		r	o	r	r	r
„ „ Exophthalmus ..	o	o	?		r	r	r	r	r
Termites	o	o	o		o	r	o	o	g
Hard Back Grubs	o	o	o		o	L	o	o	o
Froghopper	L	-	-		-	-	-	-	-
Mealy-Bug	o	o	g		o	o	o	g	g
Grasshoppers	o	o	r		o	r	L	L	o
Beetle	o	o	r		o	o	o	o	o
Cane Fly	o	o	o		o	o	o	o	r

INSECT PESTS.—(*Concluded.*)

	Grenada.	St. Vincent.	St. Lucia	Dominica.	Montserrat.	Antigua.	St. Kitts.	Nevis.	Virgin Islands.
Sweet Potatoes.									
Scarabee - Jacobs		r	o	o		gL	r	r	r
Caterpillars		o	L	o		gL	o	l	L
Thrips		o	r	o		o	o	o	o
Red Spider		r	o	o		o	o	o	o
Slug		o	L	g		o	o	o	o
Bush Bugs		o	g	o		o	o	o	o
Hard Back Grubs		o	o	o		r	o	o	o
Tannias, Dasheens. Eddoes.									
Hard Back Borer			gL						
Lacewing Bug			g						
Yams.									
Scale Insects	L	g	g			g	r		
Slugs	o	o	g			o	o		
Hard Back Grubs	o	o	o			r	o		

	Grenada.	St. Vincent.	St. Lucia	Dominica.	Montserrat.	Antigua.	St. Kitts.	Nevis.	Virgin Islands.
YAMS BANANAS AND PLANTAINS.									
Marasmius Rot.	o		G						
CACAO.									
Root Diseases	l		gg L						
Canker	gg L		G	gg L					
Black Rot of Pods	o		gg	gg					
Brown Rot of Pods	gg L		Ggg	gg					
Die-back and Stem Diseases ..	l			o					
Pink Disease	o		l	o					
Thread Blights	o								
Horse-hair Blight	l								
COCO NUTS.									
Bud Rot	o	o	l	o				l	
Red Ring Disease	gg L	o	o	o					
Leaf Diseases	o	o	l	o	o	o	o	o	o
CORN (INDIAN).									
Rusts	o	gg	gg	o	o	gg	o	gg	gg
Smut	l	gg	o	o	o	l	l	l	l
Root Disease						l	o	o	r
COTTON.									
Soft Rot of Bolls	o	gg	o	o	gg	o	l	o	o
West Indian Leaf Mildew ...	o	gg	gg	o	L	gg	gg	gg	gg
Bacterial Boll Disease	o	o	o	o	o	o	o	gg	l
Angular Leaf Spot	o	gg	l	o	?	o	l	gg	o
Black Arm	o	o	o	o	o	o	o	o	o
Internal Boll Disease	o	gg	o	o	r	gg	r	gg	G
GROUND NUTS.									
Root Disease	o						o		
Leaf Rust	o	gg	gg	o	o	o	o	l	o
Leaf Spot	o						o		

PLANT DISEASES —(*Concluded.*)

	Grenada.	St. Vincent.	St. Lucia	Dominica.	Montserrat.	Antigua.	St. Kitts	Nevis.	Virgin Islands.
LIMES AND OTHER CITRUS TREES									
Black Root Disease	o	o	r	l				o	
Red Root Disease	o		o	l				o	
Unidentified Root or Collar Disease	gg L		o	r	o	o		o	
Die-back	G	o	l	L	o	o	o	o	o
Seedling Diseases	l	o	L	r	r				
ONIONS.									
Bacterial Disease				r		r	o	o	r
SUGAR-CANE.									
Root Disease	o	gg	G	o	o	gg	gg	gg	gg
Rind Fungus	o	gg	gg	o	o	gg	o	l	o o
Red Rot	o	o	o	o	o	o	o	o	o
Pine-apple Diseases	o	r	r	o	o	r	o	o	o
SWEET POTATOES.									
Root Disease	o				o		o	o	
White Rust	o							o	o
YAMS.									
Tuber Disease	o				o	o	o		
Wilt Disease	r				o	o	o		
PHANEROGAMIC PARASITES.									
Love Vine	gg L	gg	gg L	r	gg	r	l	r	r
Mistletoe	gg L	o	gg	l	o	o	o	o	r

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